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ABSTRACT

In June 1987, the National Aeronautics and Space Administration (NASA) Administrator established the Office of Exploration in response to a national need for a long-term goal to energize the civilian space program and stimulate the development of new technology. This document describes work accomplished in developing the knowledge base that will permit informed recommendations and decisions. Major sections included are: (1) "Pathways to Human Exploration" (describing three strategies in the space program); (2) "Human Exploration Case Studies" (including four case studies on expeditions to Phobos and Mars, the lunar observatory, and the lunar outpost with background and strategy, scenario, and requirements); (3) "Case Study Results and Assessment"; (4) "Exploration Program Implementation Strategy" (illustrating four phases during 1980 to 2010); (5) "Approach to International Cooperation"; (6) "Recommendations"; and (7) "Future Horizons." (YP)

Beyond Earth's Boundaries

HUMAN EXPLORATION OF THE SOLAR SYSTEM IN THE 21st CENTURY

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HUMAN EXPLORATION
OF THE SOLAR SYSTEM
IN THE 21st CENTURY

1988
ANNUAL REPORT
TO THE ADMINISTRATOR

THE OFFICE OF EXPLORATION
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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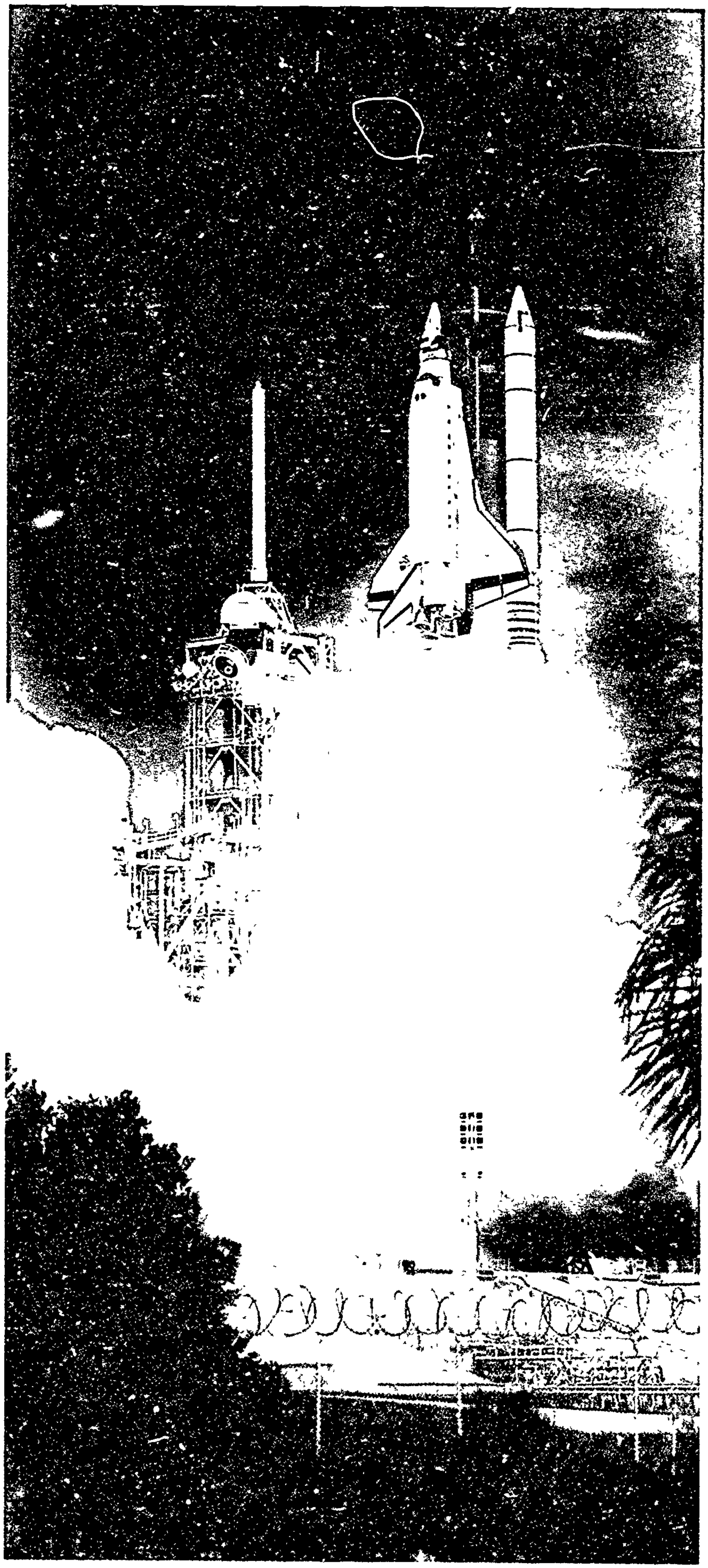
America triumphantly returned to space as the Shuttle *Discovery* soared into orbit on September 29, 1988.



PREFACE

Nearly two decades have passed since the United States established preeminence in space by sending human explorers to walk on the surface of another world. In the years following the final *Apollo* Moon landing in 1972, the civilian space program concentrated on developing a space transportation system and science and applications missions. Today, however, human exploration of the solar system is the focus of considerable attention. Once again, the United States and other spacefaring nations are placing a priority on human expeditions far beyond the confines of Earth.

"To expand human presence and activity beyond Earth orbit into the solar system."

The Presidential Directive on National Space Policy, signed into effect on January 5, 1988, establishes a thrust that will launch the United States toward visionary accomplishments in space. The policy states that a fundamental objective has been, and continues to be, space leadership, specific goals are set forth that will guide our Nation toward that leadership. Of particular significance is the directive that sets the long-range goal "to expand human presence and activity beyond Earth orbit into the solar system." The U.S. now has an explicit national mandate that challenges us to move beyond Earth's boundaries. With the full support of the citizens of this Nation, this policy goal will transcend the terms of any President, member of Congress, or NASA manager well into the next century.

In the 21st Century, mankind will most likely witness the first human footprint on the surface of Mars. We may also establish the first outpost on the Moon, to operate a research station and develop lunar resources. The choices are many; the question facing this Nation today is how America should pursue the opportunities and reap the benefits promised by human exploration of the solar system.

Human exploration is an undertaking of significant proportions, for which preparations must begin today. To achieve such ventures in the first decade of the 21st Century, we must build in the 1990s a strong, solid foundation on near-term investments in technology development, life sciences research, robotic precursor science missions, an augmentation of our launch capabilities, and a sustained commitment to Space Station *Freedom.*

Other nations are aggressively laying the groundwork for their advancement into the solar system. The United States can and must do the same, in order to lead the way, or to play a significant role in this endeavor. As the late C. Stark Draper once wrote to former NASA Administrator James Webb, "Some countries have tried to hold a position of high influence on the basis of an existing static superior level of ability. The failures of these attempts are recorded many times in the history of mankind. When for any reasons, a mighty nation has ceased to travel the path of progress, it has always been passed by rivals who continue to strive for advancement. . .'

With a strong national commitment, the coming years will bring all the capabilities necessary to send our next generation of human explorers to the Moon or Mars. The foundation is already being built. The Shuttle is flying again, and is also complemented by a fleet of

expendable launch vehicles. With our international partners, we are beginning to develop Space Station *Freedom*, which will give us a permanent human presence in space by the mid-1990s. National space policy states that America's goal is to expand human presence and activity into the solar system, and directs NASA to develop the advanced Pathfinder technologies that will allow us to realize that goal.

This is an auspicious time to raise our sights, to move forward on the path of progress, and to enthusiastically embrace the long-term aspiration of human exploration and expansion into the solar system.

John Aaron

John Aaron,
Assistant Administrator for Exploration
November 1988

INTRODUCTION

In June 1987, the NASA Administrator established the Office of Exploration in response to an urgent national need for a long-term goal to energize the U.S. civilian space program and stimulate the development of new technology. This demand had its origins in a recently intensified emphasis on long-range program planning, which was given new impetus by two reports.

In 1986, the National Commission on Space published its report, "Pioneering the Space Frontier." This Commission was appointed by the President and mandated by Congress to formulate a visionary agenda to lead America's civilian space enterprise into the 21st Century. After conducting detailed research and hearing nationwide testimony, the Commission recommended to the Nation a bold plan. "To lead the exploration and development of the space frontier, advancing science, technology, and enterprise, and building institutions and systems that make accessible vast new resources and support human settlements beyond Earth orbit, from the highlands of the Moon to the plains of Mars."

Later that year, the NASA Administrator asked scientist and astronaut Sally Ride to lead a task force to look at potential long-range goals of the U.S. civilian space program. The program was then at a crossroads, aspiring toward the vision of the National Commission on Space, but faced with the realities set forth by the Rogers Commission. It was critical for NASA to respond aggressively to the challenges of both, while recognizing the necessity of maintaining a balanced space program within reasonable fiscal limits.

The task force report, "Leadership and America's Future in Space," was released in August 1987. The report identified and reviewed four initiatives that could direct the civilian space program to a position of leadership in a particular sphere of space activity. The four initiatives were: (1) Mission to Planet Earth, elements of which NASA's Office of Space Science and Applications is now pursuing; (2) Exploration of the Solar System, robotic missions also being pursued by the Office of Space Science and Applications; (3) Outpost on the Moon; and (4) Humans to Mars.

The Office of Exploration originated from the group's recommendation that NASA establish a focal point to fund, lead, and coordinate studies of human exploration of the solar system. Building on the two initiatives featuring piloted exploration – Outpost on the Moon and Humans to Mars – the Office now heads a NASA-wide effort, the goal of which is to identify viable alternatives and provide recommendations for an early 1990s national decision on a focused program of human exploration.

The intent of this effort is two-fold. First, we seek to develop a mature understanding of the available opportunities and options. Second, we want to use that understanding to define and stimulate judicious investments in required near-term NASA programs. The investments made today will position this Nation to wisely choose and pursue a strategy for human exploration, and will enable significant accomplishments before the end of the first decade of the 21st Century.

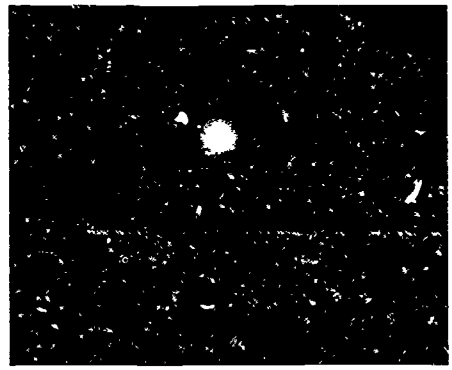
"To lead the exploration and development of the space frontier, . . . beyond Earth orbit, from the highlands of the Moon to the plains of Mars."

The choice of a program for human exploration is an important one, and one that must be made carefully. We are looking at a wide range of opportunities and their interaction with the complex set of elements – technology, life sciences research, robotic precursor missions, transportation capabilities, in-orbit assembly, extraterrestrial systems, and others – that delineate the range of possibilities.

This document is an annual report describing work accomplished in developing the knowledge base that will permit informed recommendations and decisions. An in-depth discussion of this year's studies is available in a separate three-volume series titled, "Exploration Studies Technical Report: FY 1988 Status."

PATHWAYS TO HUMAN EXPLORATION

National space policy has established the goal of human expansion into the solar system, but beyond that, no specific guidelines exist regarding the pathways, timing, or concentration of purpose. We could go to the Moon, or to Mars and its moons, or we could go first to the Moon, and then on to Mars. We could choose a plan for permanent habitation, or one for a faster mission with no lasting facilities. Intellectual reasons for exploration could dominate, or a desire for commercial gain could prevail. To formulate a logical plan to achieve the goal of human exploration, it is important to first identify and comprehend the rich array of possibilities before us. Developing a philosophical viewpoint that articulates our underlying motivation will direct the more pragmatic aspects of our activities as we progress toward meeting our objectives.



The worlds of the inner solar system, in particular the Moon and Mars, hold out their mysteries and their riches for our exploration. We have only to decide where and when to go, and what we wish to achieve when we arrive.

During a period of intense competition for Federal resources to support major science and technology research programs, it is imperative that NASA present a compelling case for the important role that human space exploration performs for the Nation. As NASA's first Administrator, T. Keith Glennan, once commented, "How can we decide how important it is to spend, on an urgent basis, the very large sums of money required to put man into orbit or to explore the atmosphere and surface of Mars or Venus unless we have a pretty firm grasp on what the purpose behind the whole space effort really is? . . . who is thinking about (this) and doing something about developing some answers?"

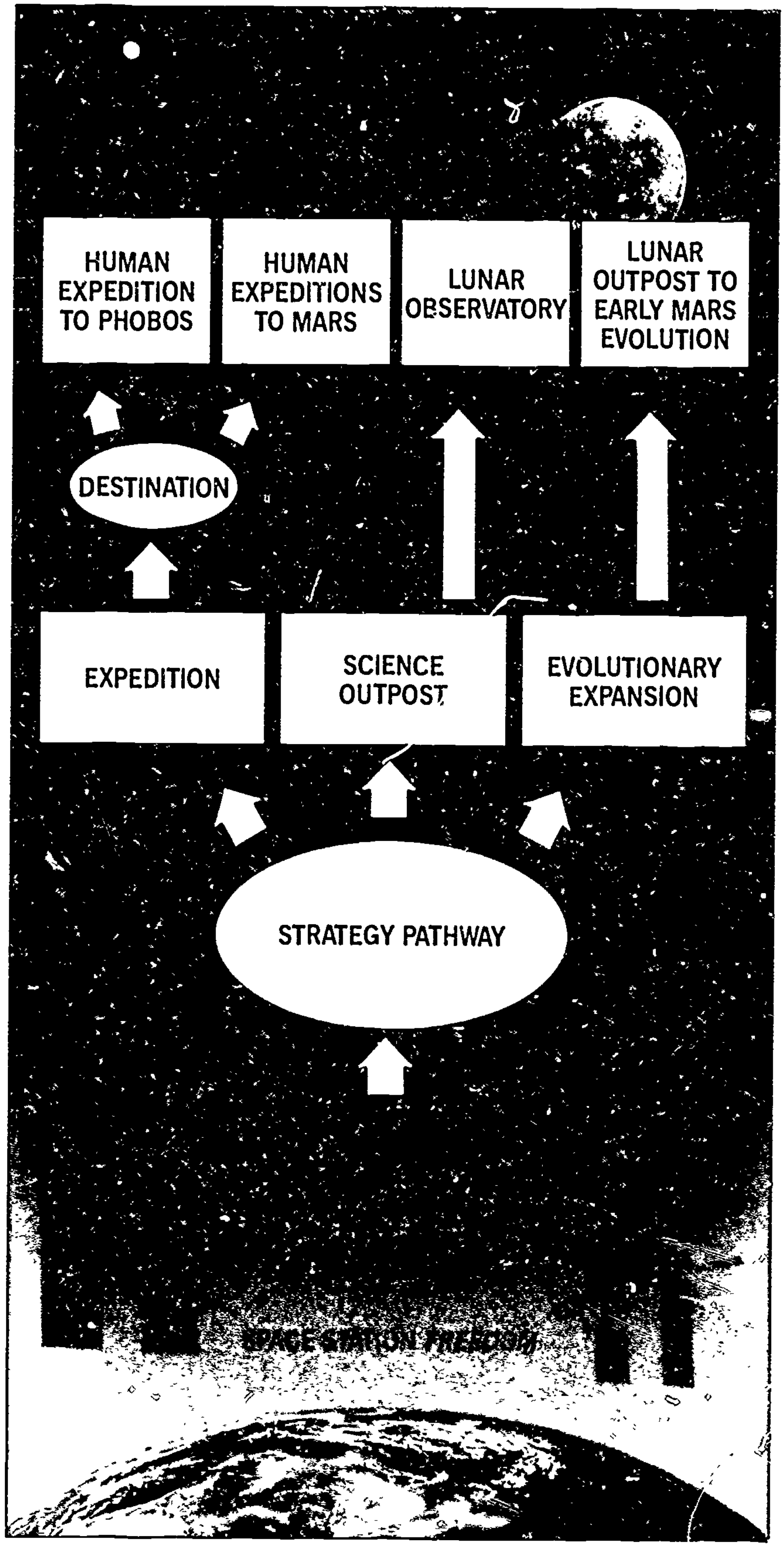
To begin to address these questions, we have reviewed seven major themes and rationales for exploration: national pride and international prestige, advancement of scientific knowledge, technology catalyst, economic benefits, space enterprise, international cooperation, and education and excellence. An awareness of the ways in which meeting the objectives embodied in these themes can be especially enhanced by human intellect, energy, and participation helps to guide the selection of potential pathways for human exploration.

Each proposed human exploration scenario must be examined in terms of how it satisfies the themes or rationales for which such missions are intended and undertaken. In order to elicit and sustain widespread support for our long-range goals, we must understand these concepts in light of the fundamental values held by our society.

An extensive range of possibilities exists for human exploration and development of the Moon and Mars. To organize and systematically examine a full spectrum of options, we identified three strategies, or alternative pathways, for study this year. Each strategy presents particular opportunities for satisfying defined exploration themes and objectives. In the coming years, additional pathways will be developed to expand the set of options.

The first strategy addresses ***human expeditions***, emphasizing a significant, visible, successful effort to establish the first human presence on another body in the solar system. The expeditionary pathway would lead to exploration without the burden and overhead

FIGURE 1. Exploration Pathways



associated with lasting structures and facilities. This pathway has been explored for missions to Mars and its moons.

Establishing a ***science outpost***, the second strategy, emphasizes advancing scientific knowledge and gaining operational experience by building and maintaining an extraterrestrial outpost as a permanent observatory. Such a facility, located far from the obscuring effects of Earth's turbulent atmosphere, would tremendously enhance our long-term astronomical studies. The experience gained in the process would serve as a foundation for establishing a permanent human base on another planetary body. This pathway has been explored for a mission to the Moon.

The third pathway, ***evolutionary expansion***, would sustain a methodical, step-by-step program to open the inner solar system for exploration, space science research, extraterrestrial resource development, and, ultimately, permanent human presence. This strategy would begin with an outpost on the Moon and progress to similar bases of operations on Mars and its moons.

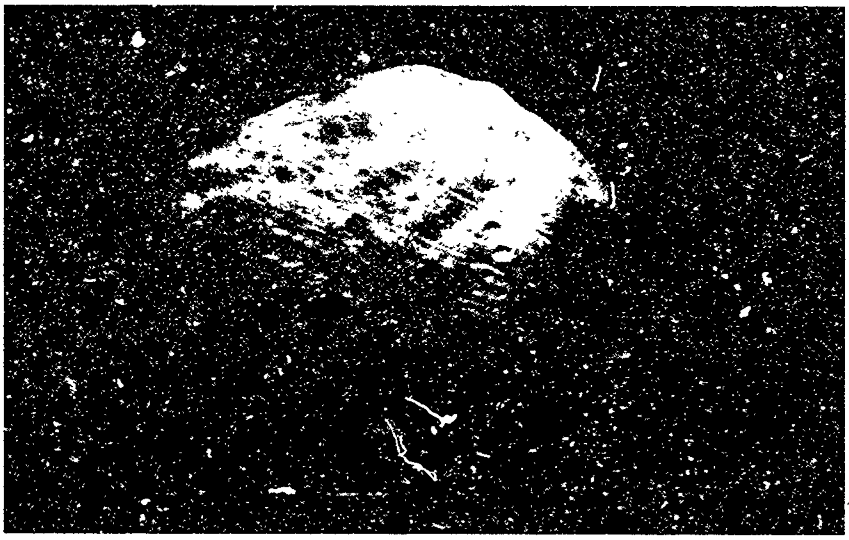
Figure 1 depicts these three pathways for human exploration of the Moon and Mars. All roads begin with Space Station *Freedom*, as an essential base for conducting life sciences research and for learning to build and operate large facilities in space. *Freedom* is also required as a transportation depot, where space transfer vehicles will be assembled and fueled, and from which crew members will embark on their interplanetary journeys.

For each of the three exploration pathways, candidate missions were identified to be systematically examined as "case studies," in order to obtain an understanding of the implications of the potential approaches to exploration. Four candidates were developed: (1) Human Expedition to Phobos, (2) Human Expeditions to Mars, (3) Lunar Observatory, and (4) Lunar Outpost to Early Mars Evolution.

Within the case study framework, detailed mission analyses and system engineering studies were performed to define a full set of concepts and requirements for each case. These analyses included an assessment of required environmental and scientific data, Earth-to-orbit transportation needs, necessary in-space support facilities and systems, in-orbit vehicles and assembly facilities, requisite life sciences research, advanced technology requirements, and provisions for systems and activities to be conducted on the surfaces of planetary bodies.

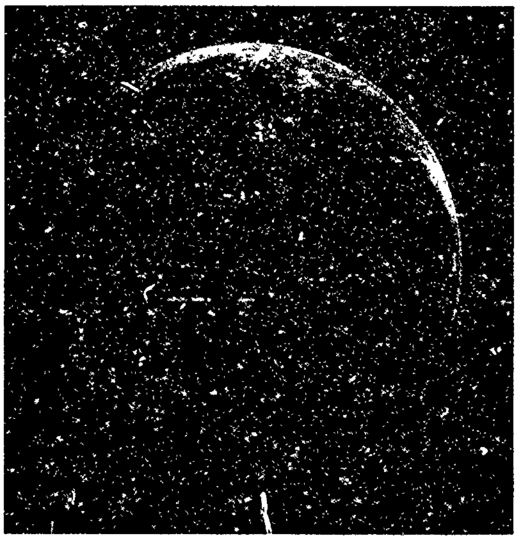
The case study effort includes producing actual system design concepts for implementing such missions. This approach builds a context within which diverse exploration strategies can be developed, analyzed, and assessed. Through building this knowledge base, it becomes possible to refine these options in the future.

One of the tiny moons of Mars, Phobos is a craggy, nearly gravity-free oval about thirteen by seventeen miles in size. Closer to its parent planet than any other known satellite, Phobos moves in an almost circular orbit 3,700 miles above the Martian surface. In this *Viking* photo, a large crater, Stickney, is visible at the lower right.



This photograph was taken by *Viking Orbiter 2* as it approached the dawn side of Mars in August 1976. At the top, with water ice cloud plumes on its western flank, is Ascraeus Mons, one of the giant Martian volcanoes. In the middle is the great canyon, Valles Marineris, and near the bottom is a large, frosty crater basin called Argyre.

Earth's full Moon in outstanding clarity was photographed from the *Apollo 11* spacecraft during its return journey in July 1969. When the photograph was taken, the first human explorers to walk on another world were already ten thousand nautical miles homeward bound.



HUMAN EXPLORATION CASE STUDIES

Reference case studies define a set of different modes of implementation of strategic pathways, so that a reasonable range of options can be understood. The number of potential case studies is very large, but only a few can be studied in depth. Additional options can be constructed by rearranging elements or by extending the reference configurations through studies that examine the effects of varying questions and assumptions.

Case studies are deliberately set at the boundaries of various conditions in order to elicit first principles and trends toward the refinement of future options, as well as to define and refine prerequisites. The objective of this approach is to avoid making simple distinctions between exploring the Moon or Mars, but rather, to determine a viable pathway into the solar system.

The candidate options described below are presented with no order of priority, nor should it be assumed that any one will represent the final goal. In the coming years, these cases will be refined, new ones will be added, and the implementation options may be narrowed.

HUMAN EXPEDITION TO PHOBOS

(Case Study 1)

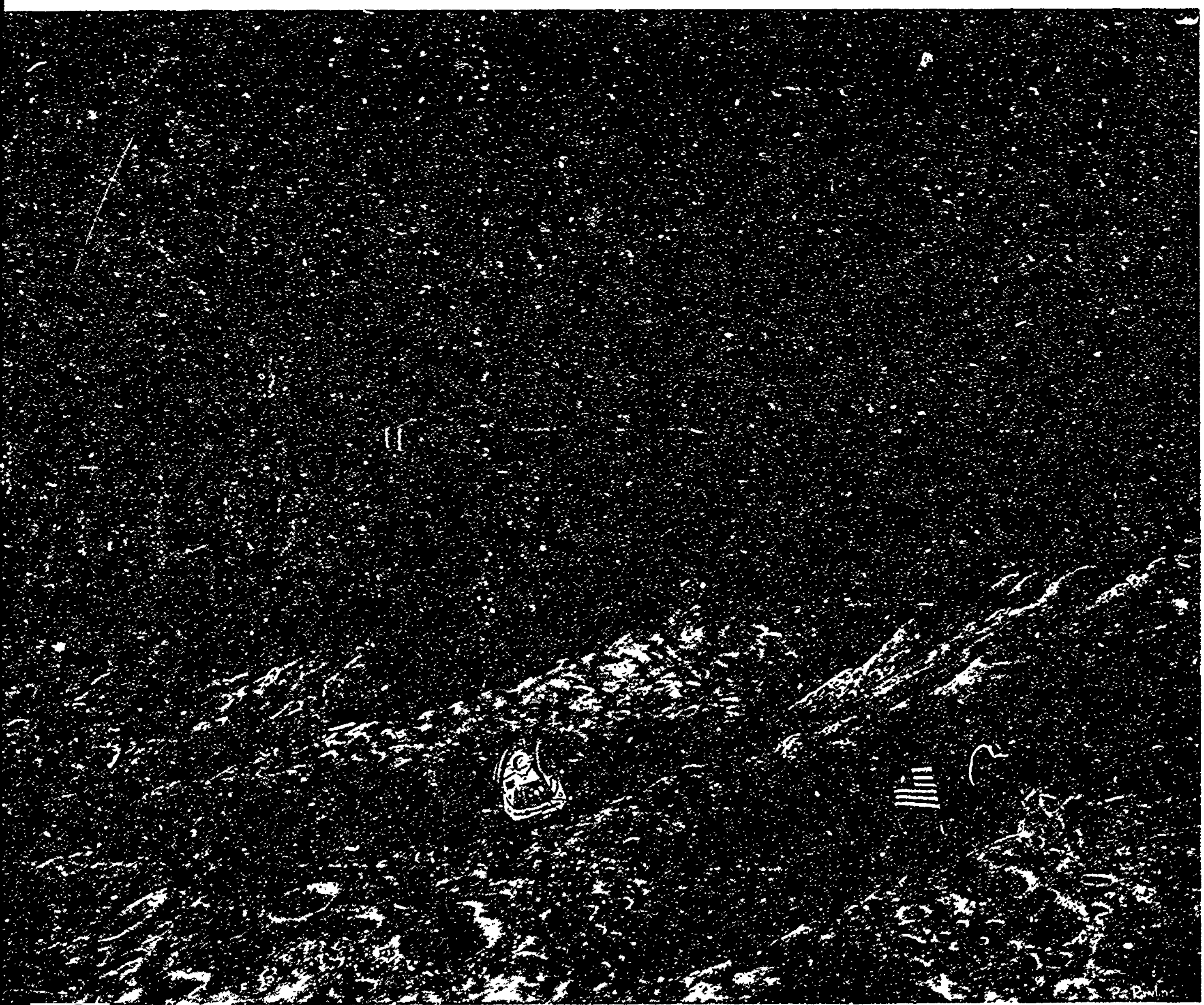
Two approaches to exploring Mars have recently been proposed and studied: (1) a human expedition, and (2) a robotic mission incorporating a highly autonomous rover. An effort to scale down the initial expedition and also achieve the objectives of both approaches has rekindled an interesting idea: a human expedition to Phobos, combined with rovers that are operated by the crew from Mars orbit. Going to Phobos would allow initially simpler, earlier human exploration of the Mars system. An expedition to Phobos would establish early leadership by sending the first human travelers to the Martian moon to explore, conduct resource surveys, and establish a science station. Also, it would provide the opportunities to conduct enhanced robotic exploration of Mars itself from the near vicinity (Mars orbit), using teleoperated rovers, pene-

Two astronauts explore the rugged surface of Phobos. Mars, as it would appear to the human eye from Phobos, looms on the horizon. The mother ship, powered by solar energy, orbits Mars while the two crew members inside remotely operate rovers on the Martian surface. The explorers have descended to the surface of Phobos in a small "excursion" vehicle, and they are navigating with the aid of a personal spacecraft, which fires a line into the soil to anchor the unit. The astronaut on the right is examining a large boulder; if the boulder weighed 1,000 pounds on Earth, it would weigh a mere pound in the nearly absent gravity field of Phobos.

trators, balloons, and sample collectors, and to return samples of both Mars and Phobos to Earth for detailed analysis. The expedition to Phobos combines human exploration objectives with those of previously studied *Mars Rover/Sample Return* (robotic) missions, but allows the capability for nearly real-time remote operation of robotic systems.

BACKGROUND AND STRATEGY

Two moons, Phobos and Deimos, revolve around the planet Mars. The *Mariner 9* and *Viking Orbiter* missions in the 1970s gave us a brief glimpse of these intriguing bodies, both of which are rather irregular in shape, somewhat elongated, and heavily cratered. They are brownish gray in color, and spectral analysis suggests that they



are composed of carbonaceous materials, similar to those of which many asteroids are made. Apparently Phobos and Deimos are chemically primitive; that is, they represent material that has remained essentially unaltered since it condensed in the solar nebula some 4.6 billion years ago. Much the same type of material evidently occurs in some asteroids, suggesting that these moons may be remnants of an initial asteroidal population.

Phobos and Deimos are thought to be similar in composition to the class of carbonaceous chondrite meteorites, which contain a substantial amount of water and carbon-containing materials. If that is true, then they offer significant potential as a source of rocket fuel for later Mars exploration missions.

Perhaps a more fundamental motivation for the proposed expedition to Phobos is to use it as a learning base for a variety of information necessary to accomplish human exploration of the Mars system. The round trip to Phobos would require the development of the capability for a long-duration space mission, which could be applied to future Mars missions. Also, because an expedition to Phobos requires fewer enabling technologies and it can be accomplished earlier than a full-scale Mars landing mission, it can serve as a valuable stepping-stone to Mars. Studying a mission to Phobos also gives us a unique opportunity to examine the techniques, problems, and special requirements implicit in the exploration of a small, essentially gravity-free planetary body. We can also begin to understand the benefits inherent in local human presence for the robotic exploration and sampling of the Martian surface.

The Human Expedition to Phobos was designed for minimum impact in terms of performance, scale, technology advancements, response time, experience, and precursors. It employs an "expedition-class" strategy; that is, no permanent human base of operations would be established. Because of the early timetable that is desired for this case, maximum use was made of planned systems and technologies that could be in place by the year 2000.

SCENARIO

An expedition to Phobos would employ a "split/sprint" transportation approach: a cargo transport carrying the Phobos exploration equipment, Mars rovers, and the crew's return chemical propellant would be launched on a minimum-energy trajectory early in the 21st Century, perhaps in 2001. In approximately nine months, the cargo vehicle would be placed in Mars orbit to await the piloted spacecraft. About 10 months later, a second spaceship carrying a crew of four would be launched from Earth on a high-energy, sprint-class trajectory, which requires about nine months to reach Phobos.

The piloted spacecraft would rendezvous with the cargo transport in Mars orbit. Two crew members would then transfer to an "excursion" vehicle and depart to explore the surface of Phobos. During that time, the crew on Phobos would make observations, conduct experiments, explore, and gather samples. The two crew members who remain in the orbiter would teleoperate, or remotely control, rovers, which would explore and gather samples from the surface of

Mars. After spending about 20 days at Phobos, the excursion crew would rendezvous with the orbiting vehicle. The Mars surface samples would be launched for return as well, and after 30 days in the Mars system, the entire crew and their supplies (using fuel transferred from the cargo vehicle) would return to Earth. The total length of the mission would be a little more than 14 months.

CASE STUDY REQUIREMENTS

It is possible that this expedition can be initiated without using an Earth-orbital transportation depot. However, two operations must take place in low-Earth orbit: mating of elements and payloads, and the transfer of propellant or complete propulsion stage exchange between Earth-to-orbit delivery vehicles and the vehicles carrying cargo and crew to the Martian system. In Mars orbit, propellant must be transferred between cargo and piloted vehicles. Therefore, the systems and techniques to robotically join elements and payloads in low-Earth orbit, and those for cryogenic propellant storage and transfer in Earth and Mars orbit must be developed.

Space missions of 14 months in duration are three months longer than the current Soviet experience on their space station *Mir*, and 11 months longer than the *Skylab* experience for the U.S. Significant research on the effects of such long exposures to low gravity and the space environment is a necessary prerequisite.

Because of the low-gravity, dusty environment of Phobos, vehicles and crew accommodations for activity in proximity to the moon, as well as outside the spacecraft, must be designed to function effectively in such conditions.

The first expedition to Phobos could occur in 2003; this would require a fast-paced development schedule and minimum dependence on in-orbit support facilities. It is possible that no robotic precursor missions beyond the *Mars Observer* planned for 1992 are required. The Phobos expedition includes a number of the objectives of the *Mars Rover/Sample Return* mission, which is being studied as a precursor to the Mars expeditions (Case Study 2).

HUMAN EXPEDITIONS TO MARS

(Case Study 2)

Sending piloted spacecraft to Mars has been an aspiration for decades; it was seriously considered (with accompanying technology investments) as early as 1969, and it has been the centerpiece of many studies since then. Recent activities by the National Commission on Space and the Ride Task Force have renewed national interest in this concept; these two studies proposed ambitious plans for piloted missions to the surface of our planetary neighbor.

This case study develops a three-mission set of expeditions to send the first human explorers to the Martian surface, thereby clearly capturing early leadership in piloted interplanetary exploration. Once there, the crew would scientifically explore the local terrain

The first human travelers to walk on the surface of Mars, a crew of two is exploring Noctis Labyrinthus in the Valles Marineris system of enormous canyons. It is just after sunrise, and on the canyon floor four miles below, early morning clouds can be seen. The frost on the surface will melt very quickly as the Sun climbs higher in the Martian sky. The astronaut on the left is a planetary geologist seeking to get a closer look at the stratigraphic details of the canyon walls. On the right, the geologist's companion is setting up a weather station to monitor Martian climatology. The astronauts have traveled to this site in a six-wheeled, articulated, unpressurized rover

and geological formations, emplace long lived geophysical instruments, and collect samples for return to Earth. The Martian moons, Phobos and Deimos, would be explored as well.

BACKGROUND AND STRATEGY

The scientific exploration of Mars is a long-standing goal of the space community, and indeed, the planet has stimulated human imagination for centuries. When *Mariner 9* reached Mars in 1971, a fascinating, diverse world was revealed — a world with many similarities to our own Earth. The huge volcanic mountains, enormous canyons, a surface etched with evidence of ancient floods, sand dunes, ar atmosphere, variable cloud patterns, and seasonal polar caps: all are familiar characteristics. And our successful *Viking*

missions, landed in 1976, told us much more about Mars; at the same time, more questions arose to further pique our curiosity.

The 1988 U.S.S.R. *Phobos* spacecraft, and the U.S. *Mars Observer* mission, to be launched in 1992 to study the geoscience and climate of the planet, will combine with later precursor missions to set the stage for the human exploration of Mars.

The objective of this case study is to test the feasibility and potential scale of near-term human expeditions to the Martian surface. The Mars expeditions would require significant advances in technology and space operations experience and capability. The case also serves as a basis for defining additional precursor robotic missions and life sciences research, and for understanding the impact of providing artificial gravity for crew vehicles.

This is an expedition; as such, it emphasizes being the first to arrive, the use of expendable vehicles and systems, and a temporary structure on the planet. An early surge in resources would be necessary to meet minimum time schedules.

SCENARIO

Three separate expeditions to Mars are envisioned; for each, a split/sprint transportation approach would be employed. For the first expedition, a cargo transport carrying the landing vehicle (including the Mars surface habitat, exploration equipment, and the ascent vehicle) and the Earth-return chemical propellant would be launched on a minimum-energy trajectory early in the 21st Century, perhaps in 2005. Upon arrival, this vehicle would be placed in Mars orbit to await the piloted spacecraft. About three months later, a spaceship carrying eight crew members would be launched to Mars on a high-energy, sprint-class trajectory.

After an eight-month journey, the piloted craft would rendezvous with the cargo transport in Mars orbit. Four crew members would transfer to the Mars landing vehicle and depart for a 20-day exploration on the Martian surface. The other four crew members would perform the propellant transfer from the cargo to piloted spacecraft, conduct Mars-orbital science, and monitor and assist the activities under way on the surface of Mars. After approximately 30 days in the Martian system, the surface crew would rendezvous with the orbiting parent spacecraft and subsequently depart for Earth, arriving six months later. The total length of the mission would be a little more than 14 months.

Cargo/piloted vehicle pairs would again set out for Mars during the next two launch opportunities. Piloted excursions to Phobos and Deimos would also be part of the three-mission set. Each of the three Mars missions would include human and teleoperated robotic exploration, and each is planned to visit a different landing site on the Martian surface.

CASE STUDY REQUIREMENTS

The Earth-to-orbit transportation needs for expeditions to Mars are significantly greater than those required to travel to Phobos (Case

Study 1). Because of the large scale of these missions, a low-Earth orbit transportation depot would be needed to assemble and fuel spacecraft, to transfer crew members to the Mars vehicle, and to recover them upon return to Earth orbit. Technologies for in-orbit assembly operations, long-term storage of cryogenic propellant, and methods for transferring propellant while in the orbits of both Mars and Earth must be developed. Mars expeditions would also require significant new technologies, such as advanced propulsion systems and aerocapture techniques at both Mars and Earth.

After a long journey, the crew would land on Mars, which has a gravity field that is about one-third that of Earth; they will need to be physically fit and ready to explore. The length of the mission and the variation in gravitational conditions raise important life sciences issues. A program of research is required to lead to a decision on whether the mission can be carried out safely within a zero-gravity spacecraft, or whether the provision of an artificial gravity environment is necessary. If artificial gravity is required, the acceptable characteristics (gravity level, rotation rate) must be predetermined.

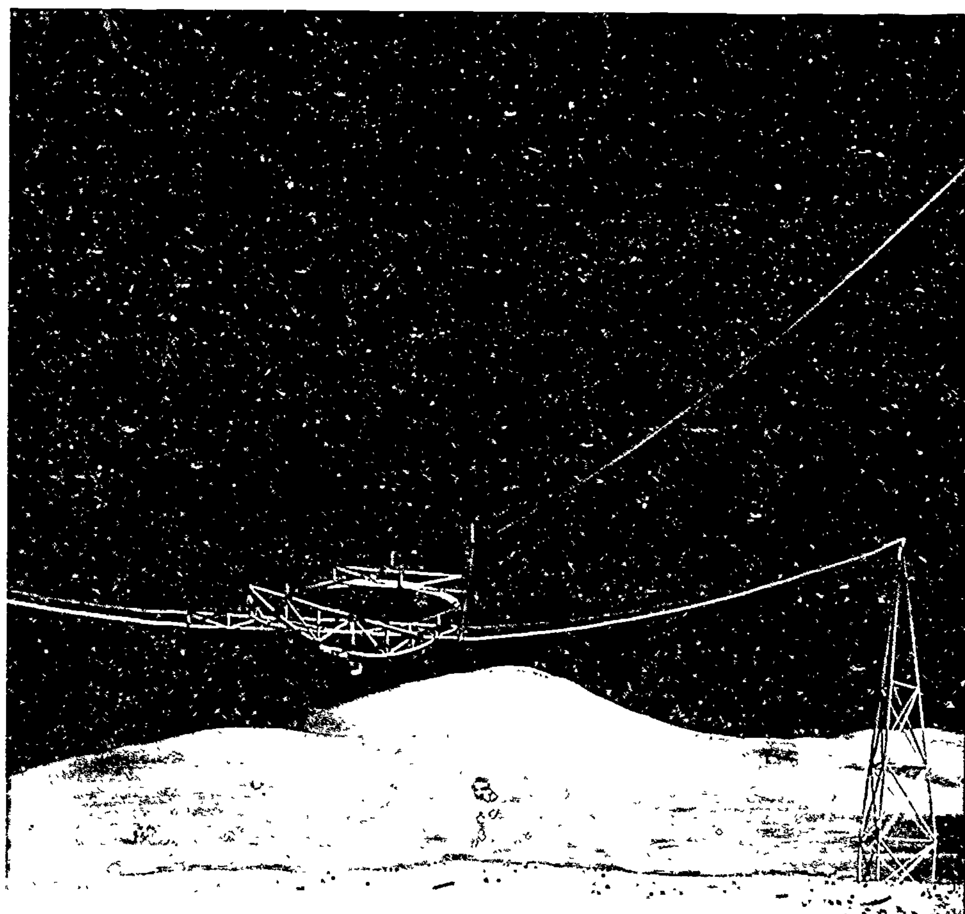
Robotic precursor missions are required to better understand the Martian environment for reasons of human safety, lander safety and operations, optimizing the scientific return, and providing end-to-end technology demonstrations for human missions.

This case would require a fast-paced development schedule in order to allow an expedition by the later part of the first decade of the 21st Century. Research for determining whether zero gravity or artificial gravity should be used may be the major pacing item for the schedule.

LUNAR OBSERVATORY
(Case Study 3)

Astronomers have long been frustrated by the fact that, even with the most sophisticated telescopes on Earth, many of the objects that they wish to observe are extremely difficult to see because of the impediments generated by Earth's atmosphere. Telescopes in Earth orbit offer substantial improvement in viewing conditions, but an observatory on the Moon could be orders of magnitude more sensitive, as larger, more stable instruments and arrays can be emplaced.

The objective of this case study is to understand the effort required to build and operate a long-duration human-tended astronomical observatory on the far side of the Moon. The Moon's far side, which is quiet, seismically stable, and shielded from Earth's electronic

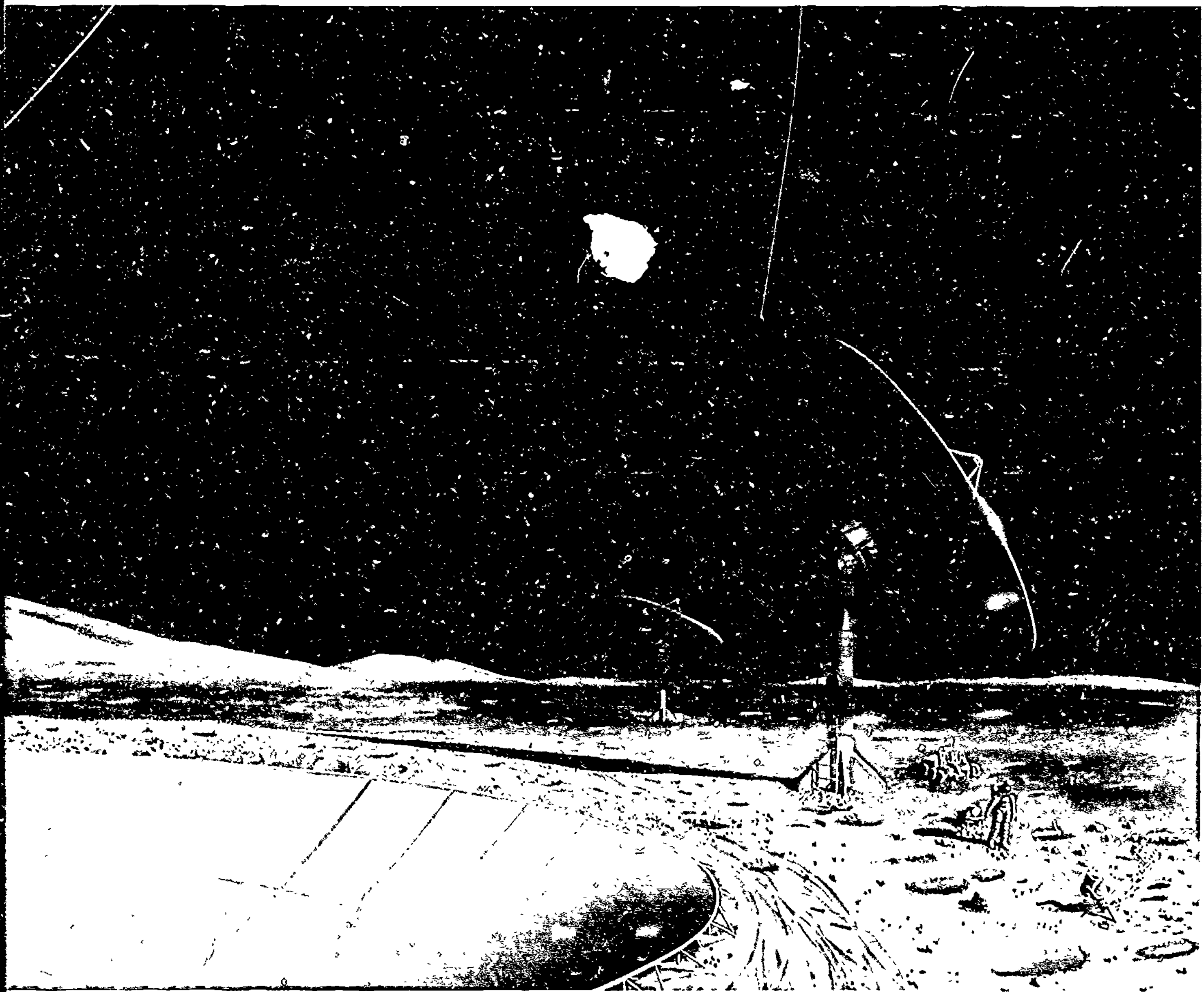


In the left foreground of this potential configuration of an observatory on the far side of the Moon, a large, fixed radio telescope is mounted in an existing crater. The telescope focuses signals into a centrally located collector, which is shown suspended above the crater. The lander in which the crew lives can be seen in the distance on the left. Two steerable radio telescopes are emplaced on the right; the instrument in the foreground is being serviced by a scientist. The other astronaut is about to replace a small optical telescope that has been damaged by a micrometeorite. A very large baseline optical interferometer system can be seen in the right far background.

noise, may be the solar system's best location for such an observatory. The facility would consist of optical telescope arrays, stellar monitoring telescopes, and radio telescopes, allowing near-complete coverage of the radio and optical spectra. The observatory would also serve as a base for geologic exploration and for a modest life sciences laboratory.

BACKGROUND AND STRATEGY

The Lunar Observatory would build on the legacy of the Apollo Program, through which we learned that human beings can visit and work on the surface of the Moon. This case represents a substantial step forward, to build and operate new and larger types of instruments and extend the range of exploration.



The Moon is a keystone for planetary science. Understanding gained from *Apollo* investigations forms the basis for interpreting the history of other planetary bodies that have only been studied remotely by robotic missions. That history is an essential element in understanding the early history of Earth, as well as providing insight into the process of evolution of all the solid bodies of the solar system. As we continue to refine our case studies, we will work intensively with the scientific community to validate and refine our understanding of the opportunities to advance science through an observatory on the Moon.

This case attempts to maximize scientific return using a minimum amount of permanent support facilities. In addition, it would provide an opportunity to gain experience in building and operating surface science systems, specifically as interim steps toward establishing a permanent human base.

Building up the observatory would include both robotic and piloted missions, with the robotic spacecraft delivering equipment and supplies to the lunar surface. The number of set-up missions per year was limited to two, in order to minimize infrastructure requirements and associated investments.

SCENARIO

The scenario for the Lunar Observatory assumes that four missions to the Moon's far side would be required to set up an operational facility. The four flights would consist of one cargo and one piloted mission per year, in two successive years, perhaps beginning as early as 2004. These four missions would be followed by one combined crew/cargo mission per year thereafter.

Each piloted spacecraft would carry a crew of four. The round trip would be fewer than 20 days, including a maximum of 14 Earth days spent by the crew on the lunar surface. No permanent habitat would be set up; because of the short stay time, and also because of the fact that non-servicing missions will visit different sites, the crew would live in and work out of the lander vehicle on each mission.

The base would be crew-tended, but not permanently occupied. Using one or more unpressurized rovers capable of traversing 10 kilometers, the crew would set up experiments and service and maintain equipment during one lunar day (14 Earth days) per visit, with no requirement to occupy the facility during the lunar night. The number of instruments, and their level of sophistication, could increase with time as our experience grows and the outpost is furbished and maintained.

Nominally, the astronomical facilities would require human-tended servicing only once every three years after they become operational. In the off-servicing years, two crew members would make several exploratory trips in the unpressurized rover, while the other two crew members would remotely control automated rovers traveling larger distances.

CASE STUDY REQUIREMENTS

A facility in low-Earth orbit would be necessary to support transfer vehicle and payload assembly operations, including element construction and checkout, propellant storage and transfer, and payload servicing. The transportation strategy also calls for the use of aerodynamic braking (aerocapture) into Earth's orbit as the crew vehicle returns to the transportation depot.

For the most part, the technology requirements for the Lunar Observatory focus on activities on the surface of the Moon. Vehicles for transporting the crew on their 10-kilometer trips must be developed. (Such vehicles will be larger than, but functionally similar to, the *Apollo* lunar roving vehicle.) Some of the telescopic systems would require specialized equipment for their emplacement. To operate the facilities and the rover, an electrical power plant must be constructed and maintained.

To establish the Lunar Observatory, an adequate far-side site must be characterized and certified for landing. This would require a precursor robotic mission such as the *Lunar Observer* already under study by NASA's Office of Space Science and Applications.

LUNAR OUTPOST TO EARLY MARS EVOLUTION

(Case Study 4)

One of the recommendations of the National Commission on Space was that a "bridge between worlds" be built in the inner solar system to establish human presence on the Moon and Mars, combining a number of different objectives in the process. An underlying goal is to learn to live, first off the lunar land, and eventually the Martian land as well. This case study seeks to realize that goal, by building a capability that would lead to a nearly self-sufficient, sustained human presence beyond low-Earth orbit. The evolutionary approach would provide the impetus for a broad range of technology advancement, evolutionary experience in outpost construction and habitation, use of local resources, and the development of facilities that would stimulate further growth.

An evolutionary approach to settling the inner solar system would begin with an outpost on the Moon. Here, just three days away from Earth, we could become experienced in living and working on another planetary body. The explorer in the foreground, wearing a constant-volume, hard space suit with rotating joints, is a representative of a commercial enterprise that intends to develop and exploit extraterrestrial resources. A lunar oxygen production plant, set between the two large solar panels, is generating a supply of rocket fuel that will be used for later journeys to Mars. The lunar base can be seen in the distance.

BACKGROUND AND STRATEGY

This approach to expanding human presence into the inner solar system addresses a variety of objectives: science, resource development, technology stimulation, and commercial benefits. Through a series of progressive steps, Earth's Moon, and then Phobos, Deimos, and Mars would be thoroughly explored and exploited.

The intent of the missions proposed in this case study is to develop and sustain a human presence beyond Earth orbit; this would be accomplished in two parts. First is the establishment of a permanently staffed facility on the lunar surface. This outpost would

provide a living environment in which to conduct partial-gravity research, gain experience in long-duration human planetary missions, and initiate the use of local resources. Lunar oxygen, for example, could support the lunar base life-support system, and could be used for rocket fuel for further expansion of exploration. Another interesting possibility is that helium-3, which is available in commercially useful quantities on the Moon, may be a potential fuel for future nuclear fusion reactors on Earth. This possibility has been initially examined and found to be promising, and will be pursued more intensively in the future.

When the lunar propellant production is secure, the strategy would progress to human flights to Mars and the establishment of an outpost there. A capability for producing fuel from extraterrestrial resources would then be developed on Phobos or Deimos in order to further reduce costly requirements for transporting propellant through space. After the first three expeditions, piloted flights could continue as frequently as every 26 months, the time cycle for Earth-Mars launch opportunities.

SCENARIO

Beginning early in the next century (approximately 2004), a series of piloted and cargo flights would embark for the Moon. The crews would travel to the Moon aboard chemically propelled transfer vehicles, whereas the surface equipment would be transported by a cargo vehicle that uses nuclear electric power. Several years would be spent in constructing a permanently staffed surface facility. Experience would be accumulated in all aspects of long-duration human planetary habitation: life sciences, psychological effects and human dynamics, exploitation of natural resources, and scientific exploration. One goal of the base would be to produce, from the lunar soil, the liquid oxygen needed as rocket fuel for subsequent Mars flights.

In approximately 2010, the branch to Mars would begin. The specific timing is left open, but in general would occur when the lunar capability is sufficient to provide enough propellant to enable the Mars missions, and operational experience and capability are at a level to ensure successful, long-duration stays. First, an electric cargo vehicle would transport the Mars surface equipment, excursion modules for transportation between Mars and Phobos, and various types of scientific equipment to the Mars system. As the spacecraft approached the Mars system, it would drop off communications satellites in synchronous orbit, send robotic explorers to Deimos, and, upon arrival at Phobos, deposit a system for producing propellant (rocket fuel). Liquid hydrogen and liquid oxygen propellants produced on Phobos would be used in the transportation scenario.

In the next Earth-Mars launch opportunity, a second electric cargo vehicle, reused from the lunar portion of the mission, would push an (unmanned) crew transport to the Moon's vicinity for fueling with lunar liquid oxygen. At this point, the cargo vehicle would push the crew transport to a holding orbit, separate, and begin its return to a

low orbit about Earth, where it would await reuse on the next ferry mission. The first crew would then be transported to the transfer vehicle, and after systems check, they would begin their journey to Mars, arriving eight months later. The nominal plan is for the crew to stay at Mars approximately one year, and return to Earth after a total mission time of nearly three years. Options exist for the crew to perform a flyby abort mission (if a problem occurs, the spacecraft can return to Earth without landing on Mars, after a total trip time of about 600 days), or to limit their stay at Mars to up to 60 days. A third option exists for a two-year stay time at Mars.

Piloted excursions to Mars, similar to the first described above, are anticipated in subsequent launch opportunities. Further cargo flights may also be necessary over the duration of the Mars base build-up.

CASE STUDY REQUIREMENTS

The evolutionary approach places major demands on low-Earth orbit operational facilities to deliver, assemble, refuel, maintain, and service interplanetary vehicles. The facilities would also be used to transfer substantial quantities of propellant arriving from Earth, and would serve as a transfer facility for crews going to and returning from planetary missions.

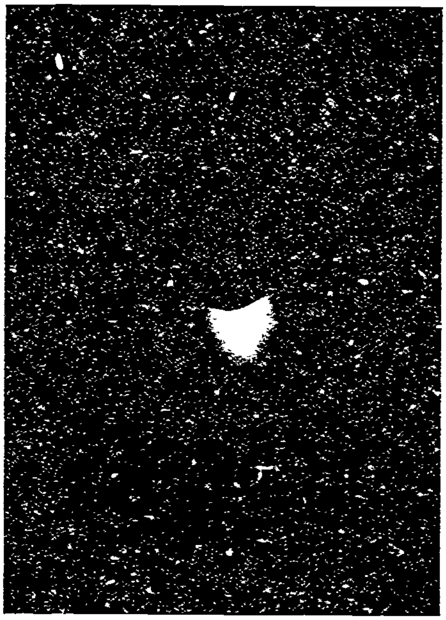
Orbital staging and refueling operations would be necessary in low lunar orbit, as well as in the vicinity of Phobos. The electric cargo vehicle would serve as a mobile node for operations outside low-Earth orbit; therefore, nuclear electric propulsion system technology to power the cargo vehicle is a major requirement Systems and techniques for aerocapture at Mars and Earth are also needed.

Additional life sciences research is required to resolve the issue of zero gravity versus artificial gravity for extended voyages to Mars. In this case, that research would be performed in the one-sixth gravity of the lunar surface. For permanent lunar and Mars bases, maximum closure of life-support systems must be provided, and significant improvements over Space Station *Freedom* life-support systems are desirable for Mars transfer vehicles.

The self-sufficiency embodied in this case levies a requirement for the development of technology and systems for mining, processing, and storing local resources. Significant power levels to operate surface habitats, resource processing equipment, scientific instruments, and surface transportation would be required; of necessity, nuclear power sources like that of the SP-100 program are the most promising candidate technologies. However, extensions to the megawatt range must eventually be made.

Robotic precursor information requirements include: global data to enable site selection for the lunar outpost; the same kind of information about Mars and Phobos to enable site selection; and engineering analyses and resource surveys for the lunar and Mars outposts and the Phobos propellant site.

CASE STUDY RESULTS AND ASSESSMENT



A variety of new vehicles must be developed to support a highway to space. This artist's conception shows a possible design for an orbital transfer vehicle, which could ferry crew and equipment between an Earth-orbital transportation depot and the Moon.

The knowledge that we sought to gain through this year's case studies lies in the areas of defining benefits returned, understanding technical requirements, and assessing near-term programs. The four cases were formulated with a consistent methodology and to a uniform level of detail, in order to compare and contrast diverse exploration strategies. As technical details and requirements began to emerge, it became possible to identify essential near-term investments in Earth-to-orbit transportation, life sciences research, robotic precursor missions, Space Station *Freedom* utilization, and technology. In many areas, the requirements are common to all case studies, therefore, programmatic readiness to meet these needs can and must be assessed before any choice of initiative is made. A key finding is that these foundation programs are pacing elements, which must begin soon in order to prepare this Nation to conduct human exploration missions in the next century.

CASE STUDIES

To develop a strong knowledge base of exploration pathway sensitivities, we selected case studies that encompass a broad range of objectives, requirements, and capabilities. All four address the prime directive of expanding human presence and activity beyond Earth orbit and into the solar system, but emphasize a different pathway, destination, or basic approach. The strategies range from one-mission expeditions to a long-term evolutionary approach. Some mission designs use existing technologies or those that will be available in the near future, others require highly sophisticated new developments. The earliest mission, to Phobos, could arrive in 2003, we could go to the Moon in 2004; and we could arrive at Mars in 2007, or as late as 2014 in the evolutionary case.

Case study results exhibit significant contrasts between expeditionary and evolutionary approaches. Expeditions are very transportation-intensive, and the major focus is on the systems and facilities required to get to the destination. For longer-term programs, operational transportation requirements are more modest and steady, and the focus is on sustained activities and systems on planetary surfaces.

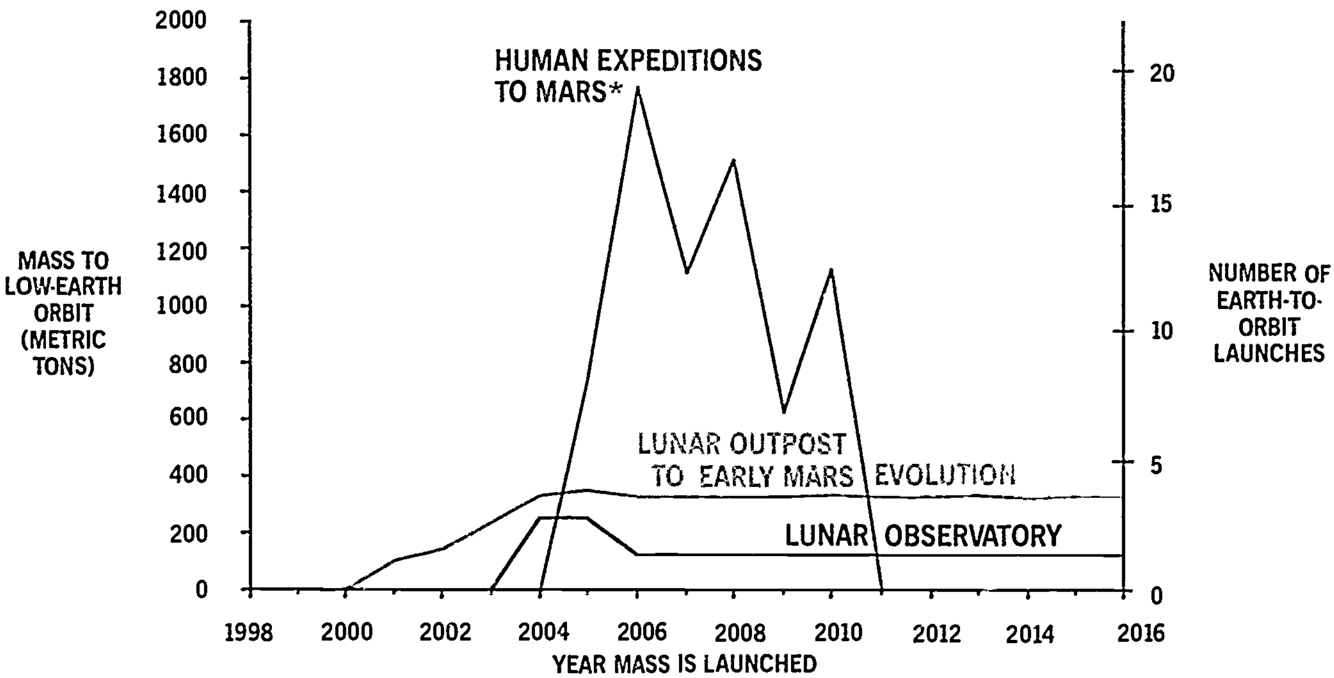
Although each case possesses its own unique attributes, some characteristics can be compared directly. For example, the annual mass to low-Earth orbit delivery requirement is important, since it directly affects the nature of necessary Earth-to-orbit transportation systems and Earth-orbital support facilities; furthermore, it is a first-order indicator of cost. Figure 2 illustrates this requirement for all four case studies, along with the approximate annual number of separate heavy-lift launches. The figure demonstrates that large peaks in mass, corresponding to the year chosen for launch, characterize expeditions. In contrast, both the Lunar Observatory and the Lunar Outpost to Early Mars Evolution cases are characterized by steady rates of much lower magnitude. All cases, however, require large total amounts of mass to be lifted to low-Earth orbit.

Another fundamental feature of human exploration missions is the need to assemble spacecraft and perform other operations in low-Earth orbit. Projecting our current experience with in-space assembly to the level required for human exploration is extremely difficult. Design expertise developed to assemble Space Station *Freedom* will provide significant insights, and the sophistication of available automation and robotics technology that can be used to assist with, or even perform, assembly operations will also be a deciding factor. In general, the areas of construction, assembly, mining, production, and operations in space and on extraterrestrial bodies present the least understood and most challenging technologies and techniques encountered.

To provide cases where the exploration is not limited by our uncertainty of operating in low-Earth orbit, the Human Expedition to Phobos was studied in a configuration that required minimum mass in low-Earth orbit. Even so, some space assembly is required, as is the transfer of propellant between a delivery vehicle or orbital tank facility and the Phobos spacecraft.

Although minimizing in-space assembly operations might be expedient to allow an interim, early mission, for evolutionary cases we envision reusable vehicles and the use of lunar oxygen for

FIGURE 2. Case Study Requirements



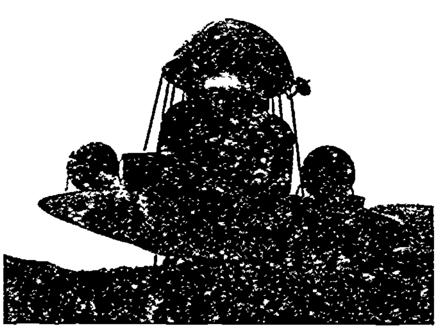
**MASS REQUIREMENT FOR 1988 CONFIGURATION NOT CONSIDERED PRACTICAL, ALTERNATIVE APPROACH BEING DEVELOPED.*

propellant and life support, plans that assume a high degree of proficiency in space operations and maintenance.

A basic issue arises from the trade that exists between assembly and transportation to low-Earth orbit: should this Nation concentrate its attention on expanding the pre-integrated mass-delivery capabilities of individual Earth-to-orbit vehicles, or should we direct our efforts to developing new technology and systems to perform significant amounts of assembly and related operations while in orbit? A complex set of interrelated parameters will determine the degree to which in-space assembly is used, but in any case, the need to bring large total quantities to orbit dictates a requirement to invest in the development of new, more capable launch vehicle systems.

We can also concentrate on minimizing the mass that must be lifted from Earth. For example, aerocapture for Mars missions can reduce that amount by about 50 percent. This technique involves the use of a large, saucer-shaped structure (an aerobrake) that is assembled in orbit. When the planet's atmosphere is reached, the spacecraft employs the resistance generated by the aerobrake to slow the vehicle down and maneuver it into orbit; little fuel is expended other than that required for attitude control. This reduces the necessary amount of propellant that must be lifted from Earth; however, the aerobrake technology must be developed, and the aerobrake itself must be assembled in orbit, also a technology challenge.

Reducing mass to low-Earth orbit stimulates other requirements in advanced technology. For example, missions to Mars benefit significantly if advanced systems, such as nuclear thermal rockets or nuclear electric propulsion, are used. These technologies take time to develop, and we must expedite our choice of an appropriate direction in which to concentrate our investments. In addition, nuclear power systems will introduce new operational requirements, complexities, and safety considerations.



The amount of mass that must be lifted from Earth for human missions to Mars can be reduced by as much as 50 percent if a structure called an aerobrake is employed. The Mars landing vehicle depicted here uses a "molly bolt" design that allows the aerobrake to be deployed in a flat shape for atmospheric entry and landing, and then retracted to form a smooth conical shape for ascent.

HUMAN EXPEDITION TO PHOBOS

If the direct route from Earth to Mars is the selected exploration strategy, a Human Expedition to Phobos appears to be a productive interim step that would provide early experience and bring us to the surface of another world more than four years earlier than a mission to the surface of Mars. Assuming the use of aerocapture for both missions, the amount of mass that would need to be carried to low-Earth orbit for the Phobos case is approximately one-third that required for a single Mars mission. Assessments of required technology indicate that the mission to Phobos can be accomplished if we assume the existence of technology already planned for that time frame, and emphasize selected new areas, such as aerobraking, cryogenic propellant transfer and storage, and technologies associated with long-duration human spaceflight.

In the process of evaluating this case, we uncovered additional promising results that indicate that the scale of the vehicles and the mission can be reduced even further. The Earth launch requirements

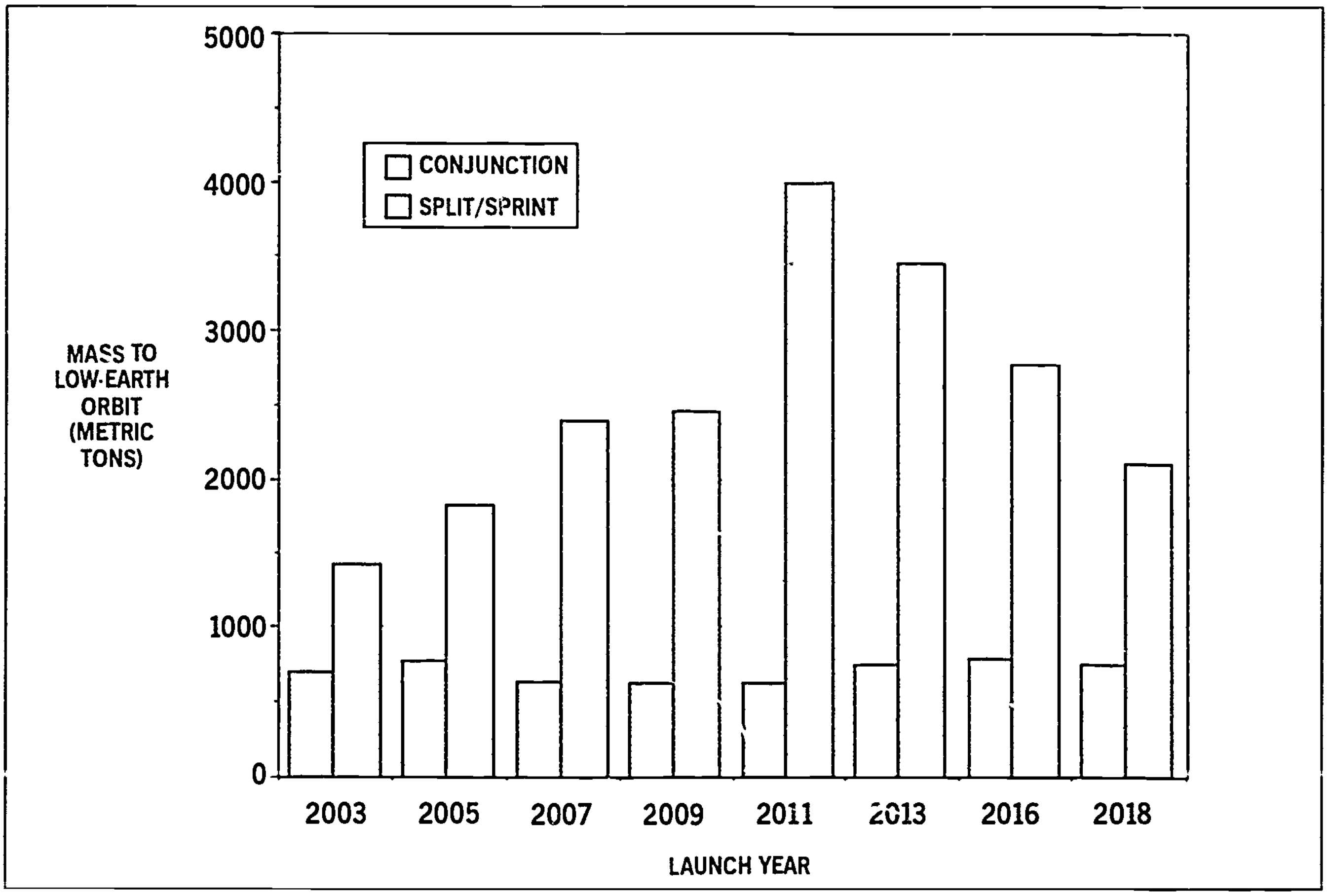


FIGURE 3. Effect of Mission Date on Mass Required in Low-Earth Orbit

can be brought within a practical range for Shuttle-derived vehicles by using aerobraking at Mars, using an integrated Earth launch vehicle/Mars transfer vehicle approach, and reducing the number of crew members.

The expedition to Phobos also serves as an excellent precursor to a later Mars landing. If the capability is developed for aerobraking at Earth, which allows reuse of vehicles, this case could evolve to a subsequent Mars landing, also without exceeding the capacity of launch vehicles derived from Space Shuttle components. An evolutionary strategy could be realized by taking a modular approach to the vehicle stages and using longer trip times (building on the experience acquired during the shorter trip to Phobos) for a Mars landing mission and subsequent evolutionary missions. In the coming year, additional study and analysis will further explore the merit of these promising results.

HUMAN EXPEDITIONS TO MARS

An expedition directly to Mars is very transportation-intensive, particularly if we seek landing opportunities at the end of the first decade of the next century. The choice of landing opportunity is important, because the performance and requirements for piloted sprint-class trajectories to Mars can vary widely with launch year and corresponding celestial geometry. **Figure 3** illustrates this sensitivity:

initial required mass to low-Earth orbit can fluctuate by as much as 60 percent. This phenomenon has a profound effect on designing spacecraft with adequate resilience to launch delays from one Mars opportunity to the next (26 months); the implications on program cost of designing a common interplanetary transport capable of capturing the mission in several consecutive opportunities are enormous. Therefore, optimum launch opportunities must be protected, or options must be developed that are less sensitive to Earth-to-Mars launch year.

Because of the number of Earth launches, the level of in-space assembly and fueling operations and the resulting cost, and the required short stay times (less than 30 days) at Mars, this case cannot be considered practical in its current form. In the coming year, much additional work will be directed toward reducing the scale of this mission. Techniques will be evaluated that involve more energy-efficient flight paths and longer stay times, advanced propulsion technologies, and incremental strategies as described for the Phobos case.

Additional analysis of robotic precursor requirements is also needed, so that we may better isolate essential precursor investments from those that enhance. Because these investments can be substantial, and the timing of required results can pace the schedule for the development of piloted missions, this analysis is critical.

Planning for the Human Expeditions to Mars also involves substantial new technology development, and unknowns of both large-scale construction and assembly in orbit.

LUNAR OBSERVATORY

The human-tended Lunar Observatory case indicates that we could establish and operate a significant scientific outpost on the Moon with a comparatively small and constant mass to low-Earth orbit. The facility could be delivered and maintained with one to two round-trip flights per year, which is compatible with Shuttle-derived launch vehicle capabilities and places minimal growth demands on Space Station *Freedom*. Science instruments, associated low-Earth orbit and lunar surface assembly and construction techniques, and the crew's ability to perform these surface operations within a 14-day stay require additional technology and operational capability and experience.

A scientific outpost on the Moon can be a productive step toward building a permanent lunar base. The evolutionary expansion process benefits from the acquired operational experience, as well as from the actual structures and facilities that would be developed. In the coming year, we will cultivate a more intense involvement with the scientific community to fully evaluate the scientific potential of this case. In addition, we will examine the idea of including the Lunar Observatory as part of an evolutionary lunar base strategy.

LUNAR OUTPOST TO EARLY MARS EVOLUTION

The evolutionary case study demonstrates the benefits to be accrued

by using extraterrestrial resources in a long-term, sustained program. Both Mars cases – the expedition and this evolution – send three piloted flights to Mars, but this evolutionary case could accomplish a Mars mission using 30 percent less mass to low-Earth orbit. The evolutionary approach appears feasible with a sustained annual mass investment that is much lower than the surge required for a direct Mars expedition; however, this savings may be offset by the required investment in facilities on the Moon. Much detailed analysis and refinement of this concept are required, especially concerning the necessary investments in technology, advanced transportation vehicles, and surface systems, before the true benefits of extraterrestrial resource use can be accurately evaluated.

The Moon can also be used as a "learning step" for exploring Mars. The lunar environment provides an opportunity to learn to live and work on another world, and to adapt to the confined, hostile environment of space. With all the unknowns associated with long-term human exploration, the Moon offers a partial-gravity extraterrestrial research base only three days' journey from Earth, and can be used as a base for developing knowledge of what is required for a long-duration mission to Mars.

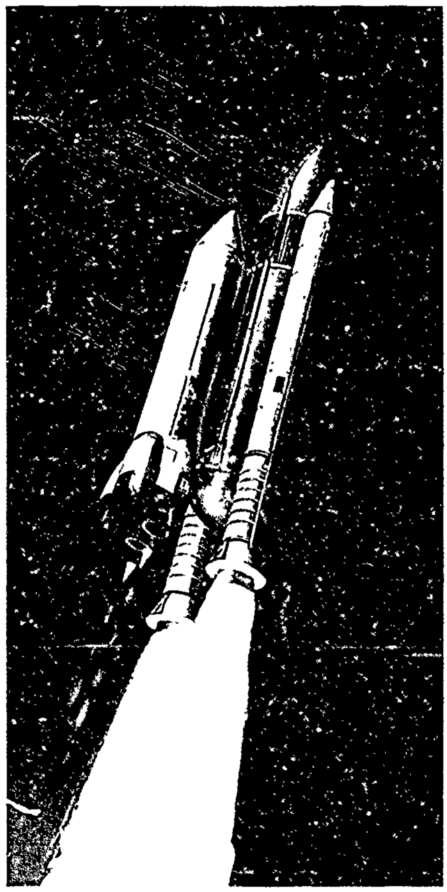
Although we have really only begun to develop and analyze this case, it shows considerable promise for scientific and exploration benefits and opportunities, as well as having the budgetary and policy advantages of a reduced and essentially constant annual requirement of resources. In the coming year, this evolutionary strategy will be analyzed in greater detail.

ASSESSMENT OF NEAR-TERM PROGRAMS

The contrast among the four case studies is not surprising, strategies were deliberately selected to cover a broad range of objectives, options, and requirements, in order to gain a deeper understanding of the fundamental needs of human exploration. The interesting conclusion about these cases, however, is that all have similar and common characteristics when viewed in terms of prerequisite foundation programs. Additional investments in existing programs are required in order to enable a full range of possibilities in the next century and to establish the foundation for human exploration, these investments share a high degree of commonality across all cases.

EARTH-TO-ORBIT TRANSPORTATION

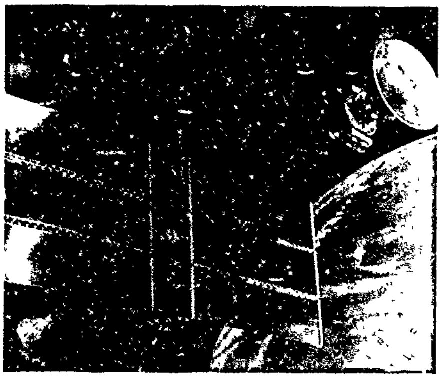
All human exploration missions will require the delivery of substantial mass to low-Earth orbit (see Figure 2); clearly, our present launch capability must be augmented. To meet the cargo transport requirements for the 1988 configuration of the Mars expeditions (Case Study 2), launch systems with an annual payload capacity for several million pounds would be required. Preliminary studies indicate that to reduce Earth-orbit operations requirements to a reasonable level, vehicles with an individual payload capacity of up to 91 metric tons (200,000 pounds) should be developed. Still, this assumes that a significant amount of in-orbit assembly is possible, an assumption that must be validated with further study.



This Shuttle-derived system concept would use existing components to significantly increase our payload capability to low-Earth orbit for unpiloted launches.

In order to meet the early Mars expedition requirements, a vehicle in the 91 metric ton class must become operational by approximately 2000. Transportation requirements for the Phobos expedition and the Lunar Observatory are much lower, and could be satisfied by an interim augmentation to the launch capacity of Shuttle-derived vehicles. As currently defined, the evolutionary case is slightly beyond this capability, and additional analysis is necessary to understand how the early phasing of the lunar buildup might be impacted if this case were initially constrained to use a Shuttle-derived launch vehicle. Studies in the next year will emphasize reducing the mass requirements, and phasing interim and advanced launch systems for exploration cases. An interim heavy-lift capability would also be advantageous for supporting prerequisite technology demonstrations and robotic precursor missions in the middle to late 1990s.

Personnel transport solutions are still under study, but enhancement of current Space Shuttle capabilities is needed, and various methods of increasing that capability must be examined. The exact degree to which enhancement is required depends on the amount of in-orbit assembly and processing that the crew must perform. Crew transport (and in-orbit accommodations) could present a major issue if significant numbers of crew members are required in addition to dedicated Space Station *Freedom* personnel. A substantial study effort is required in the next year to understand these needs and their associated sensitivities.



One concept for a vehicle to provide an artificial-gravity environment for Mars exploration crews. As shown here, the piloted vehicle is rotating around the axis that contains the solar panels. Levels of artificial gravity vary according to the tether length and the rate at which the vehicle spins.

LIFE SCIENCES RESEARCH

To permit safe, productive, lengthy stays in space, a life sciences research program to assess, understand, and alleviate the effects of long-duration spaceflight on the human physiological and psychological condition is of primary importance. In general, missions to the Moon are less demanding of prerequisite life sciences needs, primarily because of short flights and stay time, and the ability to use the Moon as a "real-time" life sciences laboratory, as in the evolutionary case (Case Study 4). Analysis indicates that with continued investment in the ongoing life sciences base research program, combined with planned research in support of Space Station *Freedom*, the Lunar Observatory and the Lunar Outpost to Early Mars Evolution cases could be initiated without additional precursor human research. (For the evolutionary case, the research required for the Mars journey is conducted during the lunar outpost phase.)

To support direct expeditions to Mars (Case Studies 1 and 2), additional prerequisite research is required in such areas as artificial gravity or low-gravity countermeasures, space human factors, long-duration health maintenance, and radiation protection. A very significant factor affecting vehicle design and crew capability is the long-term gravity environment that can safely be tolerated by the crew.

There is currently substantial uncertainty that the zero-gravity countermeasure program will provide approaches that are

satisfactory for long-duration spaceflight. Thus, an artificial-gravity research program pursued in parallel with our zero-gravity countermeasures program is a high-priority need. The results of this research must be available by 1998 to maintain a first-decade landing schedule; therefore, the lead time required dictates that this research should begin no later than FY 1990. Maintaining cooperation with the U.S.S.R. in life sciences research is essential, as this collaboration can give early indications of the zero-gravity countermeasure program's probability of success.

ROBOTIC PRECURSOR MISSIONS

Human exploration of the Moon and Mars mandates a varying number and scope of robotic spacecraft missions (precursors) that collect information to characterize planetary environments. Such missions define the conditions in which spacecraft and crew must function by acquiring valuable scientific and engineering data. Robotic missions also serve as technology and engineering demonstrations for such capabilities as landing accuracy, aerocapture at Mars and Earth, surface mobility, and autonomous rendezvous and docking. In addition, the robotic precursors demonstrate incremental capability and achievement, providing important interim milestones in a very long program. An added benefit is that building on the tradition of international cooperation through jointly conducted robotic space science missions can serve as a foundation of near-term experience toward potential cooperation involving longer-term human exploration ventures.

The *Lunar Observer*, proposed for launch in the mid-1990s, will obtain much of the information necessary to return human explorers to the Moon. The mission would map the Moon from orbit for a full year to provide complete global information about surface chemistry, mineral composition, surface features, topography, gravity, and magnetism.

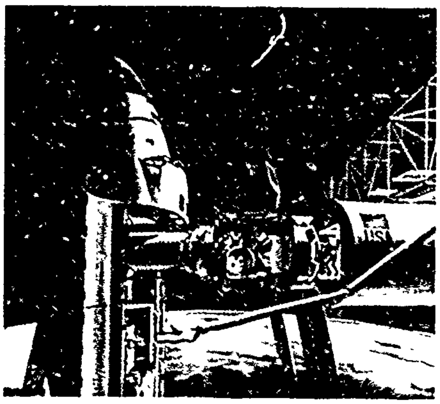
Specific precursor requirements for case studies have been defined. The Phobos expedition requires the scientific and engineering data that the U.S. *Mars Observer* (1992 launch) and the Soviet *Phobos* mission (launched in July 1988) will obtain. The Soviet probe will be the first detailed survey of Phobos; depending on the results, other precursors may be needed.

The direct Mars expedition also depends on the *Mars Observer* and *Phobos* missions. For engineering considerations, additional precursors must refine our model of the atmosphere (and demonstrate Mars aerobraking), and complement our knowledge of mechanical and soil properties on the Martian surface. To support scientific exploration, additional missions will clarify the science opportunities that can be expected and will help to develop the types of tools and techniques that can be employed in human investigations. Robotic precursors will be examined in the next year to understand mission requirements and optimum configurations.

For the Lunar Observatory, information is needed to aid in the selection and characterization of the observatory site; a modification to the currently planned *Lunar Observer* appears to provide the required data.

The *Lunar Observer* also provides site characterization data and global resource survey data relevant to the lunar phase of the

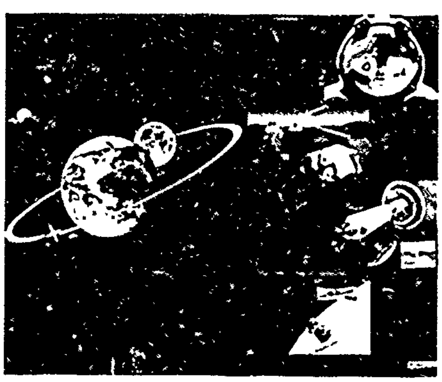
evolutionary case. Locating areas with high concentrations of resources is of utmost importance for supporting the lunar base. Depending on resource survey results, additional precursors (possibly sample returns) may be necessary in order to understand the resource extraction process that should be planned for the lunar base. Only a small part of the Moon has been mapped for resource availability and concentration; we are particularly interested in searching for areas that may hold hydrogen or water. For the Mars phase, a sample characterization of Phobos is a necessary adjunct to resource extraction development. As for any human missions to Mars or its vicinity, the *Mars Observer* and the *Phobos* missions are essential precursors for the Lunar Outpost to Early Mars Evolution case.



This artist's conception portrays a close-up view of a Space Shuttle docked to the permanently manned Space Station *Freedom*. The Shuttle is attached to a pressurized resource node that permits the transfer of crew and equipment.

SPACE STATION *FREEDOM*

As a base to gain long-duration operations experience, to conduct life sciences research, and to function as a testbed to demonstrate technology, Space Station *Freedom's* contributions to human exploration of the solar system will be monumental. Bringing these capabilities to operational status within the currently planned schedule will do much to protect our long-term options. Since Space Station *Freedom* will eventually serve as a transportation depot, it is certainly not too early to begin now to define the exploration requirements for *Freedom*. The scale of these requirements will be driven in large measure by whether the initial destination is the Moon or Mars. Therefore, in order to have the appropriate capabilities in place by the time they are needed, a pathway decision in the early 1990s is important. Space Station *Freedom* may also play a role in the development of artificial-gravity facilities, the life sciences research mentioned earlier needs to begin by 1990 to determine this. At this time, the key considerations are to begin to define reference evolution configurations consistent with our exploration case study requirements, and to develop the advanced technology that ensures readiness to enhance Space Station *Freedom's* capabilities at the turn of the century.



Project Pathfinder is developing technologies that are essential to extended human space travel.

TECHNOLOGY

A key element of our near-term investment strategy is to refine and focus the development of technologies required for human exploration through Project Pathfinder, which is pushing advanced technology in the areas of surface exploration, in-space operations, propulsion, nuclear power systems, aerobraking, automation and robotics, humans-in-space, space transfer vehicles, and many others. Because the period between initiation of technology development and readiness for actual mission application can run from eight to twelve years, it is imperative that we sustain our commitment to this advanced technology endeavor. In order to contribute to eventual mission design, the Pathfinder technologies must achieve the necessary degree of readiness by the late 1990s. **Figure 4** illustrates key technologies as evaluated in relation to the four case studies. Those technologies that are required are indicated by a circle in the appropriate column; critical pacing elements are printed in green.

FIGURE 4: Assessment of Prerequisite Technology

CRITICAL TECHNOLOGY	Human Expedition to Phobos	Human Expeditions to Mars	Lunar Observatory	Lunar Outpost to Early Mars Evolution
Cryogenic Fluid Management		○		○
Automated Rendezvous and Docking	○	○	○	○
Autonomous Rovers		○		○
Mars and Earth Aerocapture				
On-Orbit Assembly and Construction		○		○
Surface Extravehicular Activity Suits		○	○	○
Surface Power (including SP-100)		○		
Advanced Chemical Propulsion	○	○	○	○
Nuclear Electric Propulsion				
In-Situ Propellant Production				
Advanced Life Support	○	○		

In addition to component development, certain technologies will require major ground or flight demonstrations as part of the program development process. These include: aerobraking demonstrations beyond the Civilian Space Technology Initiative's Aerodynamic Flight Experiment, cryogenic fluid handling in space, closed ecological life support systems, advanced fractional-gravity spacecraft prototypes, and nuclear power systems. Communications and data handling facilities may also require some augmentation to accommodate human exploration missions.

SUMMARY

The issues discussed above – case study results and program requirements – are the outcome of initial analyses of the overall scale, breadth, and complexity of human exploration options. Although our approach has demonstrated a top-level view of what is needed to accomplish missions to the Moon and Mars, much detailed research, refinement, and sustained investments are required during the next 10 years to provide the necessary foundation to enable human exploration in the first decade of the upcoming new century.

A program for human exploration of the solar system is a productive and rewarding venture, but we must bear in mind that it is not simple and it is not inexpensive. Our analyses indicate, however, that with modest, prudent, near-term investments, and sustained commitments, this long-term goal is achievable.

EXPLORATION PROGRAM IMPLEMENTATION STRATEGY

Major human exploration initiatives beyond low-Earth orbit will require a "transportation depot" for the assembly and storage of large spacecraft. This orbital spaceport shows extensive hangar facilities for satellites, orbital transfer vehicles, and upper stages.

Developing a strategy to implement a program for human exploration of the solar system mandates the consideration of a time period of at least 20 years. Equally important are the near-term investments and studies that keep open promising options and opportunities. The implementation strategy that we have developed is built on these two fundamental factors.

A high priority is placed on positioning this Nation to accomplish exploration objectives in the first decade of the 21st Century, while, at the same time, not allowing that desire to drive required investments in the nearer term (through the 1990s) beyond levels that are considered reasonable and practical. The strategy must be sensitive to the schedules of key prerequisite programs, such as Space Station *Freedom*, which have plans extending into the late 1990s, with associated demands for technical skills and resources. Thus, our

1980

1990

PRELIMINARY PHASE

AD HOC WORKSHOPS AND STUDIES:
MISSIONS TO THE MOON AND MARS

NATIONAL COMMISSION ON SPACE REPORT:
"PIONEERING THE SPACE FRONTIER"

NASA REPORT:
"LEADERSHIP AND AMERICA'S FUTURE IN SPACE"

PHASE 1
EXAMINE MULTIPLE OPTIONS AND
INITIATE TECHNOLOGY FOUNDATION

NASA ORGANIZATION APPROACH

INTERNATIONAL COOPERATION APPROACH

FORMATION OF NASA
OFFICE OF EXPLORATION

ALTERNATIVE MISSION STUDIES

RELEASE OF THE 1988 DIRECTIVE
ON NATIONAL SPACE POLICY

BEGIN PATHFINDER
TECHNOLOGY PROGRAM

BUILD TECHNOLOGY FOUNDATION

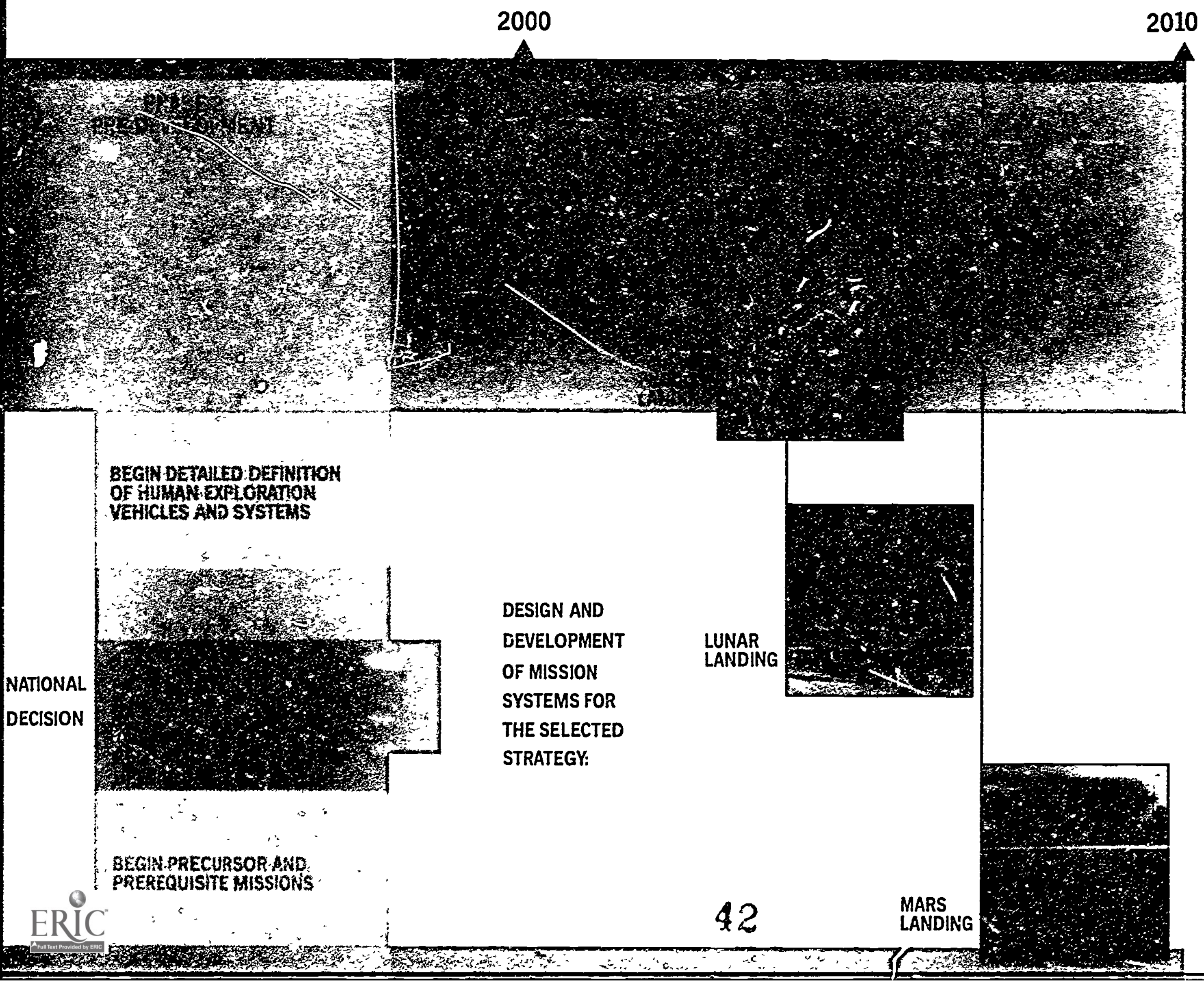
STUDIES OF PRECURSOR
MISSIONS AND PREREQUISITES

strategy must effectively build on current programs, keep the demand for exploration-unique resources at a modest level, and still preserve a capability to act in the first decade of the next century.

The program implementation strategy that meets these objectives naturally breaks into three phases: (1) defining and enabling multiple options, (2) initiating the long-lead-time development toward a specific option, and (3) developing the specific mission systems for initial exploration objectives. Each phase has defined milestones, at which points accomplishments can be reviewed and assessed. This technique is structured so that national decisions on the appropriate strategy can be made prior to proceeding to the next phase, with its increased commitment to required resources and expectations.

The strategy that we have developed is depicted graphically in Figure 5, and described in detail below.

FIGURE 5: Program Implementation Strategy



PHASE 1: Examine Multiple Options and Initiate Technology Foundation

This is the current phase of the program, which began with the release of the Directive on National Space Policy, commitment to start the Pathfinder technology program, and the formation of the NASA exploration organization. The objectives during this period are to define and enable a number of promising options, and to initiate the lengthy process of developing the technologies required to accomplish these options. Mission and system studies for the human missions, precursor missions, life sciences research, and extensions to transportation capabilities and Space Station *Freedom* are required to build a mature understanding of exploration options and their implications. These early studies serve to refine and steer long-lead-time technology developments undertaken in near-term NASA programs. Many of the investments required to keep a wide range of options open are common across defined cases, a fortuitous characteristic that allows Phase 1 resource requirements to be kept to a very reasonable level, considering the scale of human exploration ventures.

At the completion of this phase, a comprehensive understanding of the options in terms of technical and policy benefits, as well as an estimate of costs and program schedules, will be available. The information will support a decision on a strategy of going to either the Moon or Mars first and a definition of specific objectives. Having accomplished the necessary planning and studies, an approach to international cooperation on precursor science missions and prerequisite life sciences research is also decided as part of this milestone in preparation for the actual hardware start of those programs.

A national decision on an exploration pathway is assumed to occur in the early 1990s. Delaying a decision will cause an increase in resource requirements for the parallel continuation of options, which get larger with time; a delay could also necessitate a corresponding yield on the timeline for exploration accomplishments.

PHASE 2: Pre-Development

The selection of the pathway signals the beginning of the pre-development phase of the program. During this time, we commit to and begin to develop the appropriate precursor and prerequisite missions, initiate the specific definition of extensions to the Earth-to-orbit transportation and Space Station *Freedom* programs, and begin the detailed study of human exploration vehicles and systems. Also during this time, the "proof of concept" and demonstration of selected, but significant and new, technologies and capabilities are begun. This activity includes flight tests, as well as major ground tests in system-level configurations that demonstrate capabilities and technology performance, prior to a commitment to full-scale program development.

Phase 2 is estimated to require five to seven years; at the conclusion of this period, a decision to commit to the development of the actual

human exploration mission systems is appropriate. Having invested in the aforementioned studies, the result will be a mature understanding of the cost, schedule, and benefits of the missions, with a capability to build the systems in a reasonable amount of time, with low risk to cost and schedule.

Also as part of this phase, key answers to life sciences questions and concerns, as well as the characterization of the Moon and Mars, will be acquired and understood. This information potentially drives the technical and operational configuration of mission hardware, and it is thus very important to resolve these issues before committing to building the systems.

Case study analysis indicates that a Phobos expedition could be realized in 2003, a lunar base could become operational in about 2005, and a piloted Mars expedition could land in 2007. The activities conducted during the second phase of our program implementation strategy make it possible to realize these response times while keeping required resources to a modest level during the 1990s.

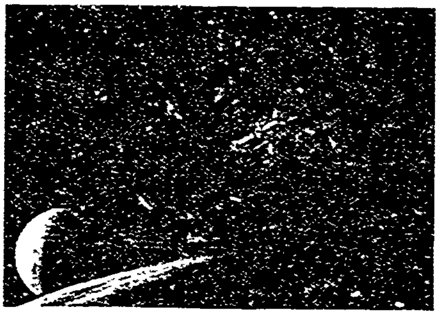
PHASE 3: Development of Mission Systems

Phase 3 is initiated with the actual development of human exploration mission systems and augmentations to supporting programs, such as Earth-to-orbit transportation, Space Station *Freedom*, and Operations Systems. This milestone, estimated to occur in the 1998-1999 timeframe, is the point at which a commitment to increased resources would be needed for the actual development and flight phases of the exploration program.

Overall, this strategy keeps investments to what is estimated to be a modest level through the 1990s while still making significant progress toward objectives. The necessary upturn in required resources does not occur until about the year 2000.

Although the funding levels will be a function of the actual strategy selected at Phase 2, this program implementation strategy would accommodate a selection of any one of the four case studies analyzed without changing the logic or assumptions contained in this strategy. It is anticipated that additional case studies will be examined that will also fit this general implementation plan.

APPROACH TO INTERNATIONAL COOPERATION



The most extensive international cooperative space effort to date, Space Station *Freedom* will benefit from the contributions of the European Space Agency, Japan, and Canada.

Throughout history, the achievement of challenging exploration endeavors has been a fundamental measure of leadership in the world. With the opening of space as a new frontier, a nation's ability to accomplish far-reaching objectives follows this tradition, and space is recognized as an important arena in which to demonstrate excellence and continued achievement. Although space exploration has had its elements of competition, most notably in the race to the Moon in the 1960s, it has also been an area of productive and increasingly complex international cooperation.

In the report, "International Space Policy for the 1990s and Beyond," the NASA Advisory Council Task Force on International Relations in Space concluded: "International cooperation, a feature of the civil space program from its outset, has served the foreign policy, scientific and space programmatic interests of the United States very well. It has given substance to U.S. leadership. The climate, character, and circumstances for cooperation have changed dramatically in recent years with the changing environment of international relations in space. However, cooperation will be even more important in the future although likely to change in character." The changing environment and character the Task Force was referring to include the growing capabilities of spacefaring nations around the world and the increasingly complex, multilateral endeavors being undertaken.

The National Space Policy also recognizes the value of international cooperation and calls for expanding our cooperative efforts in space. The Policy specifically mandates NASA "to promote international cooperative activities. . . that enhance the security and welfare of mankind."

In September 1988, the U.S., nine European nations, Japan, and Canada signed a multilateral agreement for the development of Space Station *Freedom*. Together, our international partners are expected to invest more than $7 billion in the program; the U.S. investment is expected to total about $16 billion. This is the largest international science and technology program ever undertaken. Space Station *Freedom* will be operated by an international crew and will provide valuable research data in the area of life sciences, a key element of any future human exploration into the solar system.

A logical outgrowth of the extensive participation of our foreign partners in *Freedom* – in its design, development, management, operation, and the research results obtained – could be cooperation in the human exploration of the solar system. Although it is premature to commit to any international cooperation at this early phase of our exploration studies, it is not too early to begin a dialogue with potential partners abroad. This is the same approach we took with Space Station *Freedom*. An early exchange of information with friends and allies across the broad range of precursor activities and plans for future manned projects will allow all concerned to determine the optimal match of interests for this endeavor. Such early involvement also helps to build a base of

support among our potential partner nations, so that they can identify their interests and will be prepared to join us in moving forward.

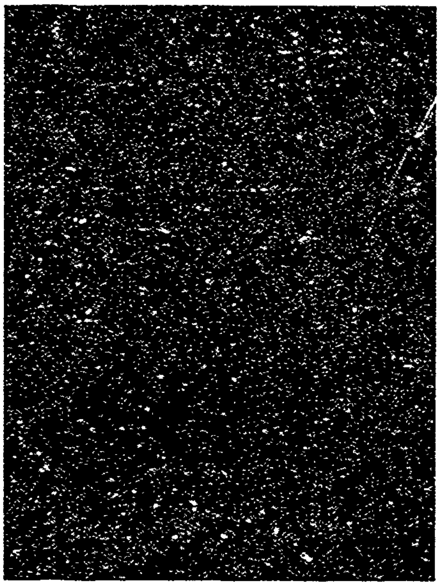
In addition to potential cooperation with NASA's traditional partners, consideration will be given to what cooperative role the U.S.S.R. could play with the U.S. in space exploration. Initial discussions with the U.S.S.R. will be limited to robotic precursor activities, rather than the broader dialogue with friends and allies with whom the U.S. has a well-established tradition of cooperation. Under the U.S./Soviet space cooperation agreement concluded in April 1987, and amended at the U.S./Soviet Summit in May 1988, both nations agreed to exchange the results of independent national studies of future robotic solar system exploration missions as a means of assessing prospects for further U.S./Soviet cooperation on such missions. The exchange of independent national studies will include *Mars Rover/Sample Return, Lunar Orbiters,* and a Lunar Science Outpost, robotic missions that could serve as important precursors to future human exploration. The exchange of results of these national studies, together with a number of precursor joint activities under way, will put us in a position to assess the desirability of cooperation with the U.S.S.R. as U.S. plans for human exploration mature.

In developing NASA's own exploration case studies, we are operating under a ground rule that participation by foreign nations may be an option, depending on their interests and capabilities. As NASA's plans crystallize, we anticipate a more active dialogue with potential partners. This will follow up on the initial contact that NASA made with friends and allies, in which we outlined the current strategies for human exploration, and will help us better understand where our potential partners' interests may lie. Eventually, we will need to jointly define the approach to any cooperation on precursor missions, provisions for the exploration infrastructure, and the development of scientific payloads.

But before this Nation can determine the best responses to the many issues of international cooperation, we must first develop a strategy that articulates what we want to gain from our space exploration program. This strategy and its goal must be developed before we enter into long-term agreements with other nations.

Therefore, we are laying the groundwork for a decision on the national approach, and in parallel, paving the way for appropriate international cooperation.

RECOMMENDATIONS



A spaceship is leaving a lunar base to journey homeward to low-Earth orbit.

For the past year, we have been examining potential pathways for human exploration, determining the technical feasibility and national impact of alternative designs and approaches. We are certain that we have developed achievable concepts for human missions to the Moon and Mars. With a modest level of investment in the 1990s, the development phase of a lunar base or an expedition to Mars could begin as early as the late 1990s.

The 21st Century will be upon us in little more than a decade. To stand ready to achieve a program of human exploration, we must begin and sustain a vital effort in detailed research, technology development, and concentrated studies. A modest, near-term investment of resources will preserve our ability to pursue a wide range of opportunities at the turn of the century, and this ability is critical to United States leadership in space.

The analysis and assessment of this year's case studies have brought to light the elements of the foundation for human exploration of the solar system. This understanding allows some specific recommendations to be made.

First and foremost, the United States must maintain and nurture a strong commitment to current, ongoing NASA programs, which are the cornerstone for future human exploration.

- **SPACE STATION *FREEDOM*** is the key to developing the capability to live and work in space much longer than we do now. Future human exploration mission plans also depend heavily on *Freedom* as a transportation depot in Earth orbit. The development, deployment, and evolutionary growth of this essential link are vital to any long-term program.
- **PROJECT PATHFINDER** is a research and technology program that will enable a broad spectrum of space missions and strengthen the technology base of the U.S. civilian space program. To preserve our options for human exploration, national commitment to Pathfinder must be sustained.
- **LIFE SCIENCES RESEARCH** is the very foundation for human habitation of space, for both Space Station *Freedom* and for long-duration exploration. A vigorous base research program in life sciences must be maintained.
- **EARTH-TO-ORBIT TRANSPORTATION** is our access to space. Now that the Space Shuttle has been restored to flight status, the highway to space must be kept open, and plans for more capable Shuttle-derived launch vehicles must go forward.
- **PRECURSOR PLANETARY MISSIONS** obtain the data that form the basis for the scientific objectives of human exploration. Robotic missions provide essential information about the environments in which human explorers and their facilities must operate, demonstrate technologies applicable to piloted missions, and serve to foster international cooperative efforts. The schedule for these missions may set the timetable for human exploration.

These ongoing NASA programs will keep open a number of options. However, to broaden the range of opportunities, we must also aggressively study and pursue strategies for augmenting some key areas.

- **A HEAVY-LIFT TRANSPORTATION SYSTEM** must be pursued and targeted for operational readiness by the turn of the century. The capability to transport large quantities of mass (equipment, propellant, and personnel) to low-Earth orbit is essential. To meet our launch needs in the middle to late 1990s, some level of interim augmentation to our existing capabilities is required as well.
- **AN ARTIFICIAL GRAVITY RESEARCH PROGRAM** must be initiated in parallel with our zero-gravity countermeasure program if we are to maintain our ability to begin exploration in the first decade of the next century. If an artificial gravity environment must be provided, the accommodation of such facilities will have a significant impact on mission configuration. Therefore, this augmentation to our life sciences research program must be made by 1990, providing an answer by 1998, to allow human spaceship design to commence.
- **AN ADVANCED DEVELOPMENT/FOCUSED TEST PROGRAM** must be planned for initiation with the selection of the program pathway. It is essential to understand the performance and capability of selected new technologies, such as aerobraking, cryogenic fluid handling in space, closed ecological life-support systems, advanced fractional-gravity spacecraft prototypes, and nuclear power systems. Experience and proof of concept in these areas are critical to a decision to proceed with the development of a specific initiative.

America's civilian space program stands at the threshold of a new era of exploration, discovery, and enterprise. We can, and must, cross that threshold, and begin to build the foundation that will allow us to break free of Earth's boundaries and soar into the worlds beyond.

FUTURE HORIZONS

Astronauts break ground for the installation of a new telescope for an observatory on the far side of the Moon.

"To explore, to discover, to understand, and to apply what we have learned for the betterment of life on Earth and in space."

A program to expand human presence and activity beyond Earth's orbit and into the solar system must itself expand, beyond NASA, out into the Nation, and indeed, throughout this planet. Sending human explorers to other worlds, to live, learn, and work, has implications that will reverberate through many facets of civilization previously touched only marginally and temporarily by NASA's programs. The possibilities are exciting and as limitless as the horizons to which our vision can extend, many of mankind's long-held dreams will become realities as Earth's representatives go to explore our planetary neighborhood.

We envision the 21st Century as a time when humanity will have broken free of the physical and psychological bonds of planet Earth to live and work for extended periods on nearby bodies in our solar system. We will have taken our first tentative steps on another planet, to establish an outpost on which visitors may learn about the universe, about how to live away from Earth, and about how to make the riches of outer space part of our lives. Perhaps we will have built a permanent research station on the Moon, where our knowledge of astronomy will be increasing by orders of magnitude. There may be an exploration outpost on Mars, where we will be probing the origin of life and climatology in our solar system. We might be mining the Moon, or Mars and its moons, or Earth-approaching asteroids, for resources that can be used for venturing farther outward, for understanding and for improving the quality of life on Earth.

Our achievements will be a source of pride for our citizens, and international prestige will rise as other nations recognize our accomplishments. America will be exploring and developing a "new frontier," carrying on the tradition in which this nation had its birth – of moving boldly forward into uncharted territory. The residents of Earth will be thrilled and inspired, as in the early days of recorded history, by the tales of other worlds that our space travelers will bring home. Young people everywhere will share in the dream, and will be drawn in ever-greater numbers to participate in its realization.

Scientific knowledge will have increased at a pace commensurate with our exploration. Our program of robotic missions will have formed a scientific foundation of information about the geology, geochemistry, atmospheres, and surface characteristics of the other bodies of the solar system, thereby significantly enhancing our understanding of our own planet as a system. The new capabilities and insights that human skills, intellect, imagination, and curiosity will bring to scientific research on other worlds will tremendously enhance this foundation, and will enable us to prove or disprove many of the theories that we have developed.

The effects of long-duration spaceflight and low gravity on the physiology of human beings will be known and understood, and we will have developed techniques to ensure that we can function safely and effectively in the environment of space. Formulating creative ways to counteract the effects of the isolation that exploration necessarily imposes on our travelers will help us to better appreciate

and meet our human needs. Perhaps we will have discovered life-forms on another planet, or the remnants of life from previous eons. Humanity's place in the universe will become more clear, and we might have discovered evidence that assures us that we are not now, nor have we ever been, alone.

Technological advances and developments will have contributed in boundless ways to our Nation's excellence and capability. We will be using extraterrestrial resources for manufacturing, energy, and radiation shielding on other planets and perhaps for economical uses back on Earth. The technology developed to enable human self-sufficiency on the Moon and Mars will have valuable applications on Earth, by accelerating advances in health care and medicine, environmental and resource management, construction, manufacturing, and many other areas.

Living in the hostile environment of space will require highly specialized technologies and systems. In this artist's conception, human explorers find themselves in the midst of a dust storm on Mars, from which their space suits must protect them.

Economically, our Nation and our planet will be reaping the benefits of technological and scientific progress. In fact, the character of our civilization may be undergoing some remarkable changes as exotic fuel extracted from the Moon is made available for use in nuclear fusion power plants on Earth. New industries will have arisen in response to the many requirements of habitation of space, and existing industries will have expanded as well. The technology that is developed to serve human needs in space could be the very foundation of many activities taking place in our Nation and on our planet in the 21st Century.

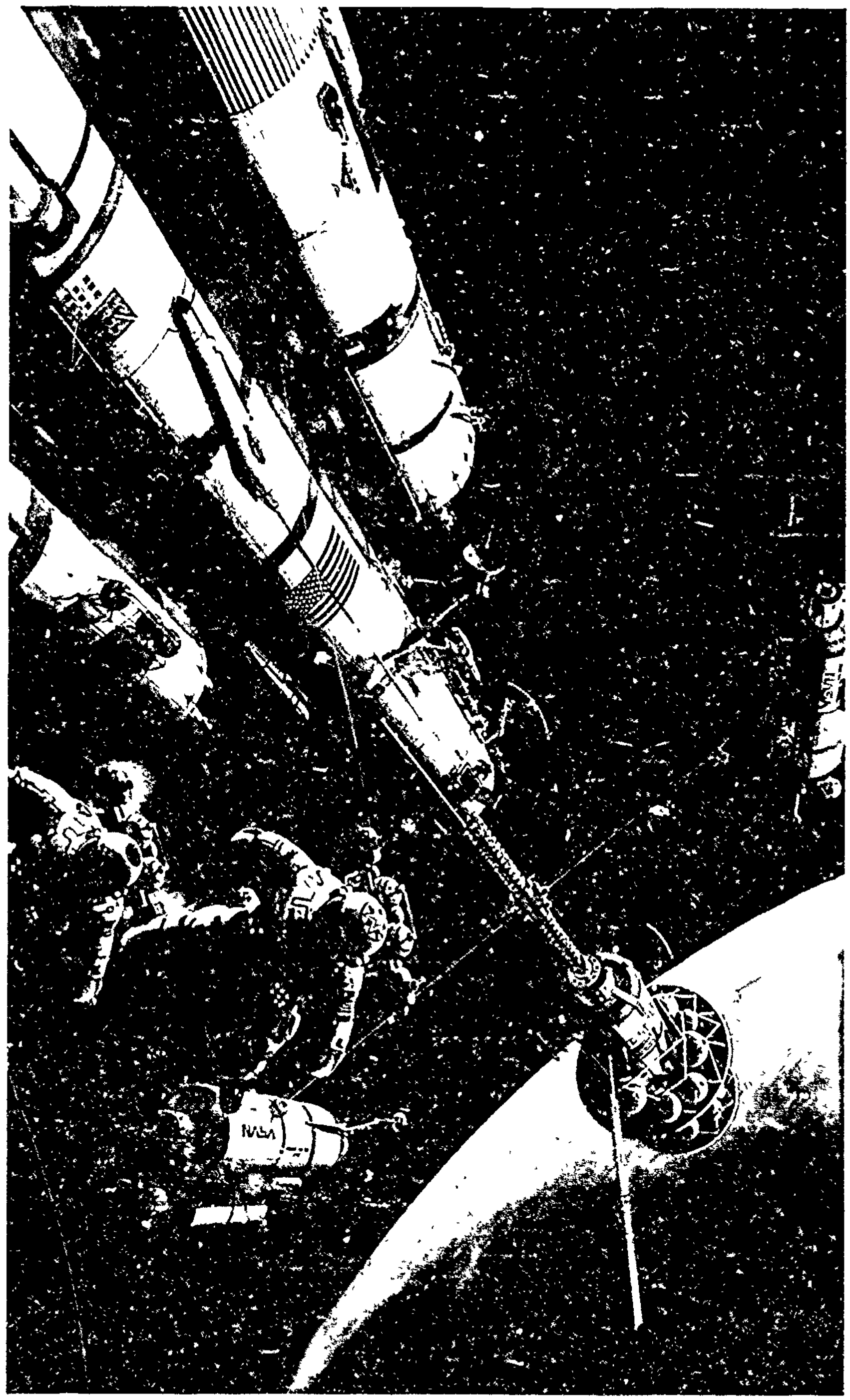
Our system of free enterprise will be invigorated as goods and services produced by private industry in response to this new area of the marketplace are purchased for use in space. In turn, the technology systems that are developed by the space program will be turned over to the private sector for manufacturing, housing, energy, and environmental needs. And the abundant raw materials to be found in the solar system will offer vast potential for extraterrestrial mining and manufacturing by private enterprise.

As more and more nations join together to explore space — the territory that cannot be claimed by any one nation — perhaps the narrow and artificial boundaries that exist on Earth will no longer matter. Major breakthroughs in science and technology will become possible, as the great minds and varying perspectives of many cultures combine to address the questions that face humanity in the future. Nations of the world may lay aside their differences and form alliances, not for defeating a common enemy, but for achieving a common goal.

To inspire and train the scientists, engineers, and humanists who will conduct tomorrow's space program, educational curricula throughout the world will change to encompass the new vistas revealed by our exploration. Even in their grade school years, children will be studying other planets, as well as their own, from the unique perspective of "being there." Learning about those worlds will become as integral a part of their education as reading, writing, and arithmetic. The fact that space is an endless frontier of mystery will stimulate the young people of the 21st Century to press

on, to learn more, to know more. The grand theme of human exploration will allow people to be connected to something that makes excellence real and tangible.

This is our vision: humanity expanding its presence and activity beyond Earth orbit and into the solar system, fulfilling mankind's aspirations to explore, to discover, to understand, and to apply what we have learned for the betterment of life on Earth and in space.



This artist's conception of a transportation depot in Mars orbit demonstrates several future possibilities: extraction of resources from Martian satellites, in-space habitats and extravehicular activity at the depot, and a docking port for excursion vehicles.

ACKNOWLEDGMENTS

Human exploration studies are supported by the skill and dedication of individuals at the NASA Headquarters program offices and at NASA field centers, private industries, and universities throughout the Nation. Although these participants are too numerous to mention individually, each valuable contribution to the success of this year's endeavor is sincerely appreciated. The Office of Exploration gratefully acknowledges all who have participated in our studies and workshops and in the development of this Annual Report. We look forward to another rich, full, productive year as we begin the second year of defining a long-term program for human exploration of the solar system.

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